ERDC/CHL TR-01-29

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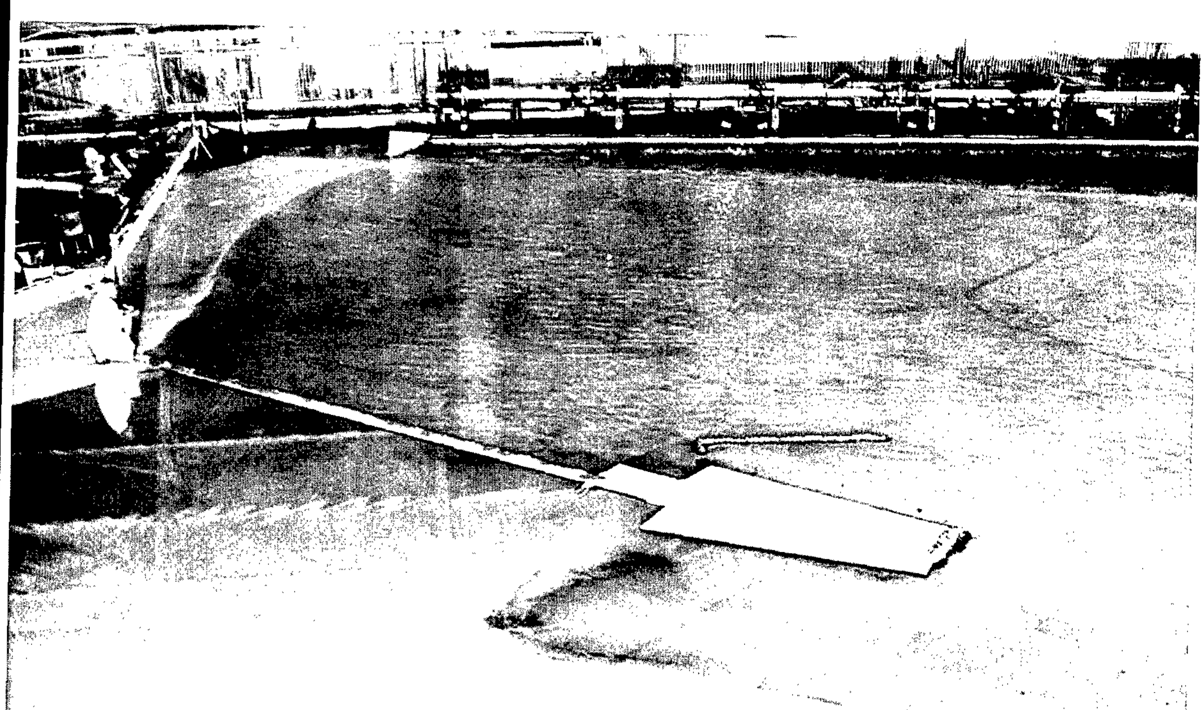
Design for Enhancement of Wave-Induced Circulation at Kaunakakai Harbor, Molokai, Hawaii

Coastal Model Investigation

Robert R. Bottin, Jr., and Hugh F. Acuff

November 2001



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Design for Enhancement of Wave-Induced Circulation at Kaunakakai Harbor, Molokai, Hawaii

Coastal Model Investigation

by Robert R. Bottin, Jr., Hugh F. Acuff

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Final report

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Fort Shafter, HI 96858-5440

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Preface

A request for a model investigation to study the impact of proposed improvements on wave-induced circulation at Kaunakakai Harbor, Molokai, HI, was initiated by the U.S. Army Engineer District, Honolulu, in a letter to the U.S. Army Engineer Division, Pacific Ocean (POD). Authorization for the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), to perform the study was subsequently granted by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Funds were provided by the Honolulu District in June and December 1999.

Model experiments were conducted at ERDC during the periods July - August 2000 and May - July 2001 by personnel of the Coastal Harbors and Structures Branch (CHSB), CHL, under the direction of Messrs. Thomas W. Richardson and Thomas J. Pokrefke, Jr., Acting Director and Acting Assistant Director, respectively, of CHL; and under direct supervision of Mr. Dennis G. Markle, Chief of CHSB. Model experiments were conducted by Ms. Kristi Evans and Messrs. Larry R. Tolliver, Glenn B. Myrick, and Hugh F. Acuff, civil engineering technicians, and William G. Henderson, computer assistant, under the supervision of Mr. Robert R. Bottin, Jr., research physical scientist. Dr. Edward F. Thompson analyzed wind data at the site and developed wave growth curves for Kaunakakai Harbor. This report was prepared by Messrs. Bottin and Acuff.

Prior to the model investigation, Messrs. Bottin and Acuff met with representatives of the Honolulu District and visited Kaunakakai Harbor to meet with the local sponsors and inspect the prototype site. During the course of the study, liaison was maintained by means of conferences, telephone communications, e-mail, and monthly progress reports. Mr. Lincoln C. Gayagas was technical point of contact, and Mr. Milton T. Yoshimoto was project manager, for the Honolulu District.

Messrs. Gayagas and Yoshimoto along with other Honolulu District staff including Messrs. James Bersson, James Pennaz, Jim Hatashima, and Mr. Randal Leong of the State of Hawaii Department of Transportation visited ERDC to attend briefings, conferences and/or observe model operation during the course of the study.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic yards	0.7646	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
Inches	2.54	centimeters
knots (international)	1.8532	kilometers per hour
miles (U.S. statute)	1.609347	kilometers
miles per hour	1.609347	kilometers per hour
miles per hour	1.467	meters per second
pounds (mass)	0.4536	kilograms
pounds (mass) per cubic foot	16.02	kilograms per cubic meter
square feet	0.09290304	square meters
square miles	2.589988	square kilometers
tons (2,000 lb, mass)	907.1847	kilograms

1 Introduction

Kaunakakai is located on the south-central coast of the Island of Molokai, County of Maui, State of Hawaii (Figure 1). Molokai is known as the Friendly Island and is located between the islands of Oahu and Maui. It rises to 1,512 m (4,961 ft) above sea level in the east. Molokai is 673 sq km (260 square miles)[1] in area and had a population of just over 6,700 in 1990. In 1873 Father Damien, the Belgium Roman Catholic missionary, began his work in the leper colony of Kalawao on the Kalaupapa Peninsula of northern Molokai. Pineapples, coffee, and cattle are raised on the island. Kaunakakai is the island's largest city.

Kaunakakai Harbor is located adjacent to Pier Island at the end of a causeway that extends seaward about 580 m (1,900 ft) from shore in a southwesterly direction. An aerial photograph of the harbor is shown in Figure 2. It consists of a deep draft port adjacent to the west side of the island and a small-craft harbor, protected by rubble-mound breakwaters, adjacent to the east side of the island. Depths are about 7.3 m (24 ft)[2] in the deep draft harbor and 3 m (10 ft) in the small-boat harbor. Prior to harbor construction, a relatively flat, shallow reef extended seaward about 975 m (3,200 ft) at the site.

Problems and Needs

The area immediately east of the causeway bordering Kaunakakai Harbor is currently a mud flat. Poor water circulation has resulted in the collection of a large amount of sediment and debris. Local residents describe conditions in the area as having steadily deteriorated from one of clear water and an abundance of coral reef and fish nearly three decades ago to its present state.

Preliminary investigations have indicated that the causes of the poor water circulation and sediment accretion can be traced to work on the existing harbor facilities as well as erosion of surrounding uplands (USAED, Honolulu, 1999). Work at the harbor included modifications to the facilites and causeway and construction of the small-boat harbor. The original pier was built on piles, which allowed currents and sediments to flow through the structure. In later years, the

[1] Units of measurement in the main text of this report are shown in SI units, followed by non-SI units in parentheses. In addition, a table of factors for converting non-SI units of measurement used in figures, plates, and tables in this report to SI units is presented on page viii.
[2] All depths and elevations cited herein are in meters (feet) referred to mean lower low water (mllw) unless otherwise noted.

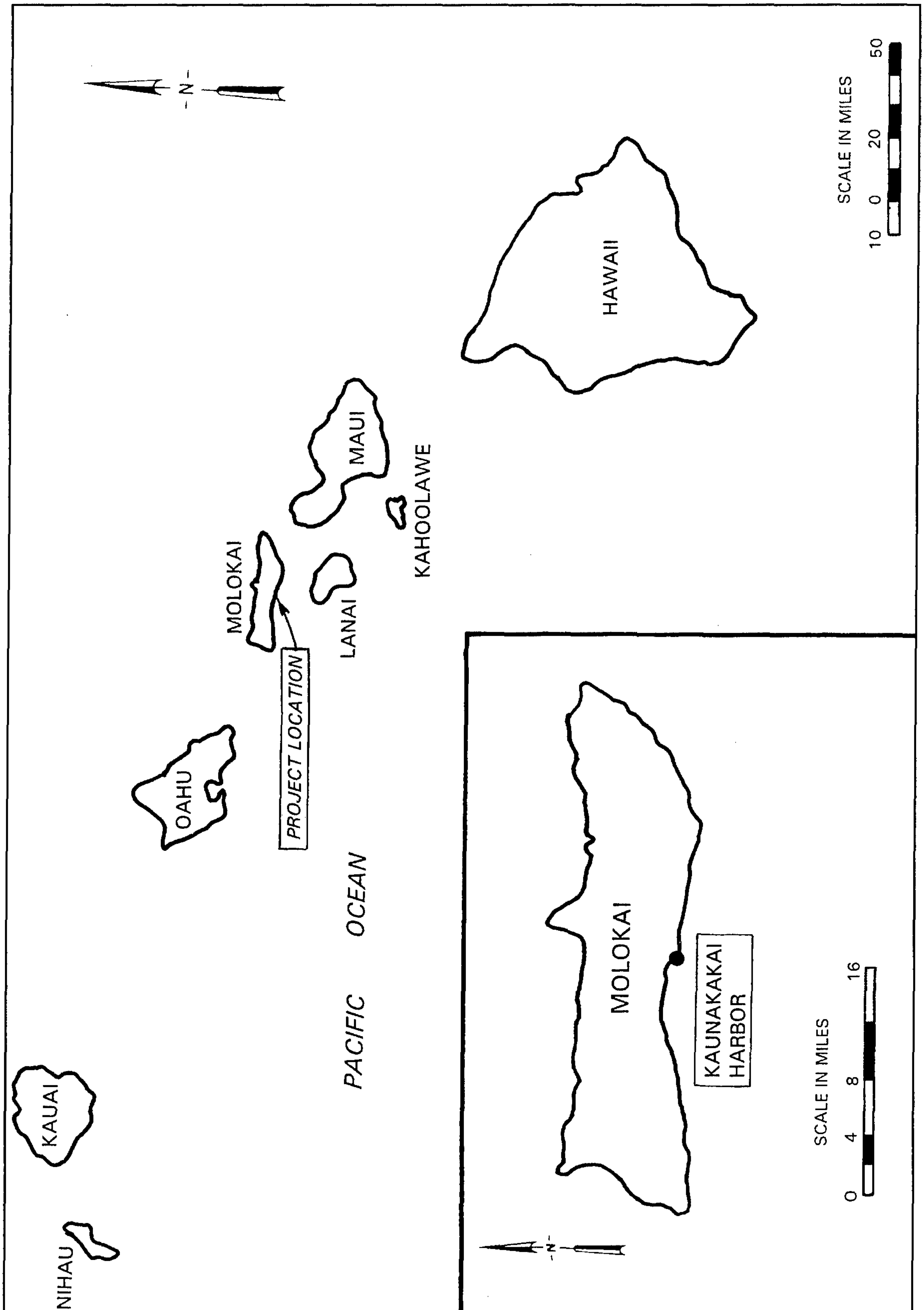

Figure 1. Project location

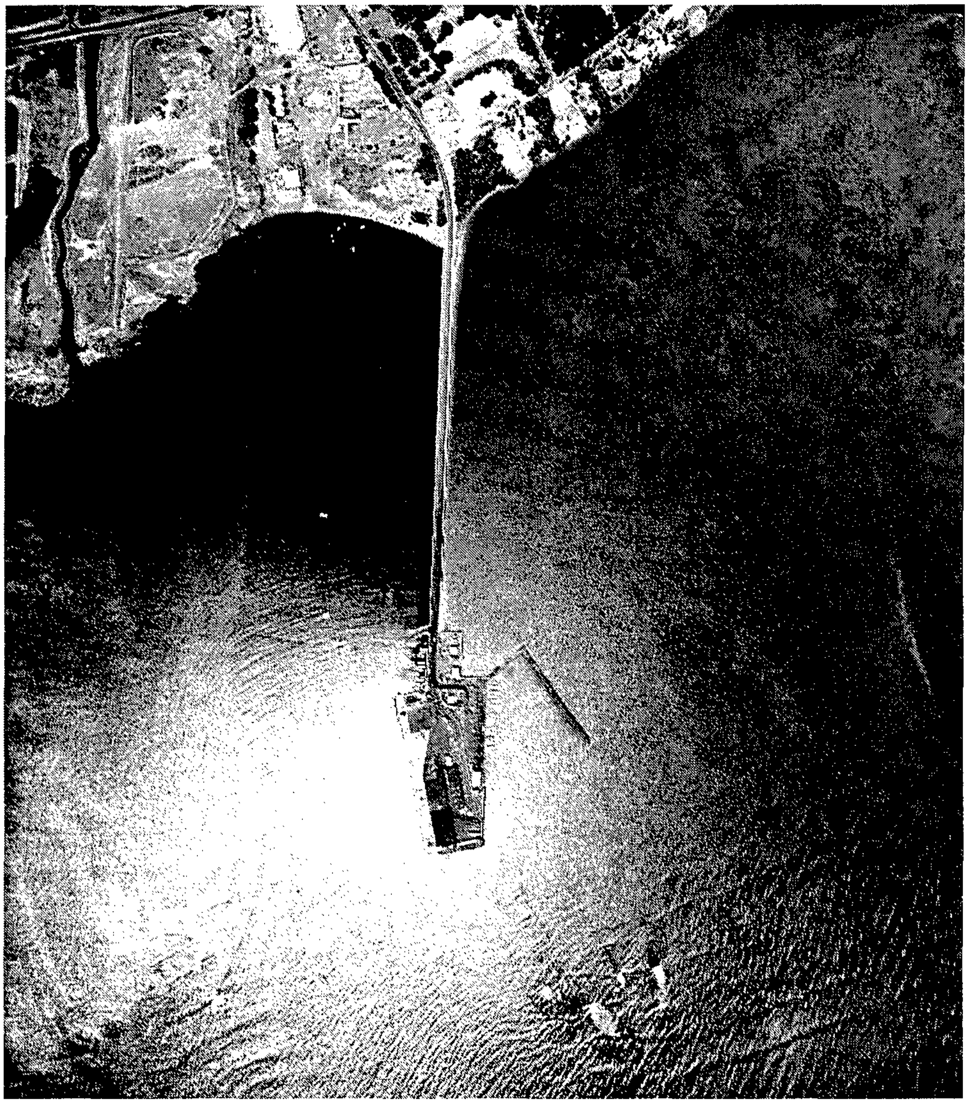

Figure 2. Aerial view of harbor

pier portion was reconstructed utilizing both piles and fill material. Subsequent modifications included extending the facilities seaward, filling the area, and building new facilities on the fill. These actions inhibited the flow of currents and sediments around and through the structure. Construction of the small-boat harbor further restricted the circulation of water around the end of the harbor facilities due to the stub breakwater constructed parallel to shore. The original causeway design included two culverts that would allow the flow of water to pass from one side to the other. However, there is no indication that the culverts were included in construction. The causeway in its present form creates a relatively impermeable groin inhibiting circulation in the area and trapping sediment east of the harbor.

The erosion of the surrounding uplands can be traced back several decades, during which time a series of brush fires resulted in the loss of enormous amounts

of vegetative cover in the area. The remaining exposed soil has since been subjected to severe erosion during storm events. With no debris or settling basins to collect the sediment, the eroded sediments are carried by runoff to the ocean and deposited along the shoreline and on the surrounding reef. Beginning immediately east of the harbor causeway and extending eastward for approximately five miles, sediments have covered the majority of the reef and created large mud flats.

To address the problems of poor water circulation and sediment buildup in the area immediately east of the causeway, the following preliminary plans were developed (USAED, Honolulu, 1999):

a. A series of precast concrete box culverts would be constructed through the causeway. The culverts would provide an outlet for longshore currents and improve water circulation in the area.

b. Approximately 465,390 sq m (115 acres) of the reef immediately east of the causeway would be dredged to depths ranging from -0.6 to -0.9 m (-2 to -3 ft). The dredged area would enhance and promote the development of coral.

c. An erosion control plan would be undertaken to decrease the amount of sediments entering the system. The plan would include the construction of settling ponds for each of the major streams and drainage outlets entering the ocean within the project area.

Coral reefs and heads consist primarily of calcium carbonate deposits. Most corals grow approximately 1-2 cm (2.5 to 5 in.) per year. It is expected that coral will repopulate the affected area after improvements are made at the site. The presence of coral in the affected area will serve to rejuvenate the entire reef ecosystem and improve environmental quality as other marine life will begin to flourish under its protective cover. Various species of reef fish that are either seldom seen, or are no longer present, in the area are expected to return subsequent to coral repopulating. It is estimated that initial recovery of the reef area will become evident approximately 1 year after improvements are made.

Purpose of Model Investigation

At the request of the Honolulu District, a coastal hydraulic model investigation of Kaunakakai Harbor was initiated by the U.S. Army Engineer Research and Development Center's (ERDC), Coastal and Hydraulics Laboratory (CHL) to:

a. Study waves, wave-induced current patterns and magnitudes, and sediment movement patterns for the existing harbor configuration.

b. Determine the impacts of the proposed box culverts and dredged basin adjacent to the causeway on waves, current patterns and magnitudes, and sediment patterns in the area.

c. Optimize the number, sizes, and locations of culverts required in the causeway to provide enhanced wave-induced circulation.

d. Develop remedial plans for the alleviation of undesirable conditions as necessary.

e. Determine if design modifications to proposed plans could be made that would significantly reduce construction costs without sacrificing the desired level of protection.

2 Model

Design of Model

The Kaunakakai model (Figure 3) was constructed to an undistorted linear scale of 1:75, model to prototype. Scale selection was based on the following factors:

a. Depth of water required in the model to prevent excessive bottom friction.

b. Absolute size of model waves.

c. Available shelter dimensions and area required for model construction.

d. Efficiency of model operation.

e. Available wave-generating and wave-measuring equipment.

f. Model construction costs.

A geometrically undistorted model was necessary to ensure accurate reproduction of wave and wave-induced current patterns. Following selection of the linear scale, the model was designed and operated in accordance with Froude's model law (Stevens et al. 1942). The scale relations used for design and operation of the model were as follows:

Characteristic	Model-Prototype Dimension[1]	Scale Relations
Length	L	$L_r = 1:75$
Area	L^2	$A = L_r^2 = 1:5,625$
Volume	L^3	$V_r = L_r^3 = 1:421,875$
Time	T	$T_r = L_r^{1/2} = 1:8.66$
Velocity	L/T	$V_r = L_r^{1/2} = 1:8.66$
Discharge	L^3/T	$Q_r = L_r^{5/2} = 1:48,714$
[1] Dimensions are in terms of length (L) and time (T).		

The existing small-boat harbor breakwater and wave absorber along portions of the causeway are rubble-mound structures. Experience and experimental research have shown that considerable wave energy passes through the interstices of this type structure; thus, the transmission, reflection, and absorption of wave energy became a matter of concern in the design of 1:75-scale model. In

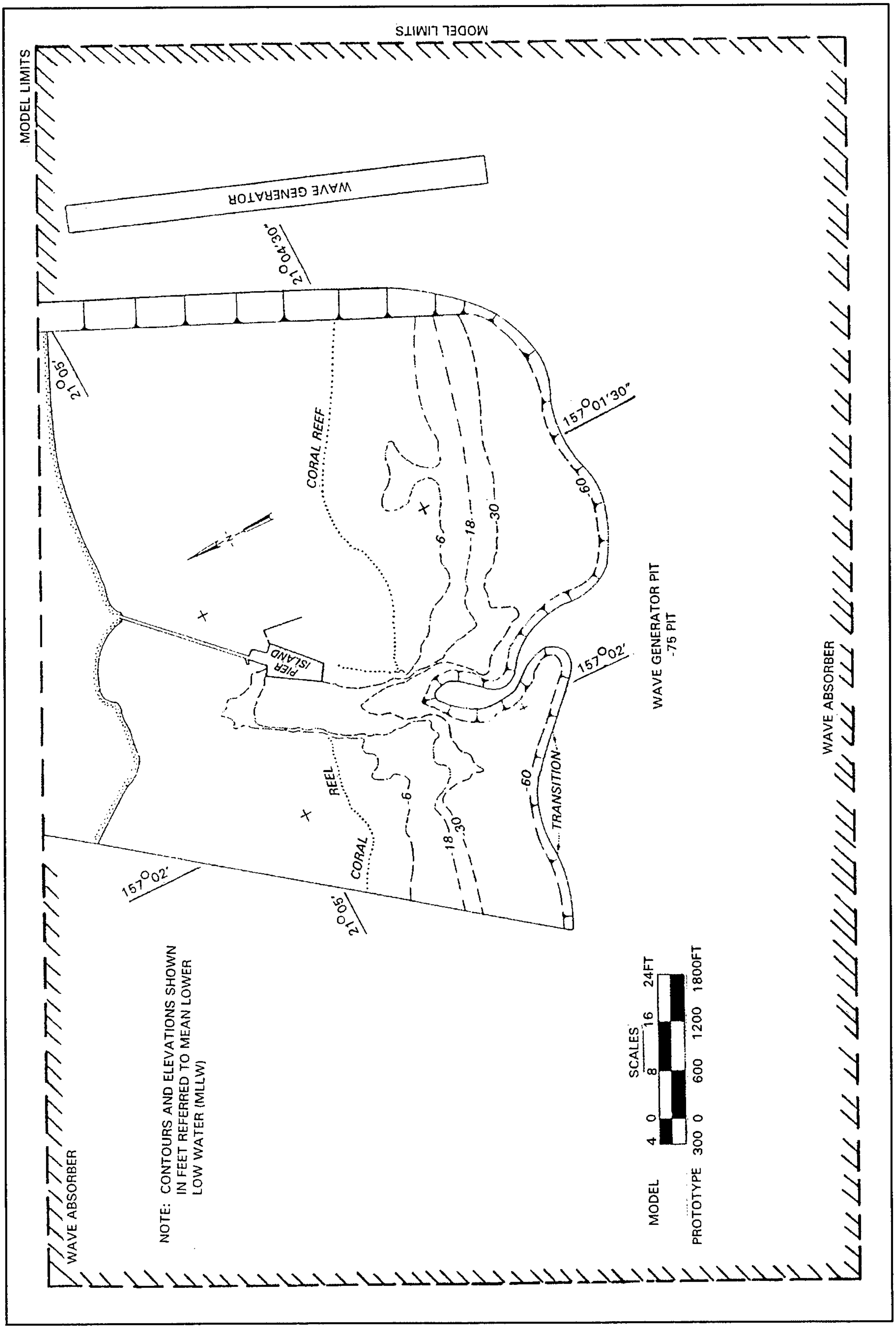

Figure 3. Model layout

small-scale hydraulic models, rubble-mound structures reflect relatively more and absorb or dissipate relatively less wave energy than geometrically similar prototype structures (LeMehaute 1965). Also, the transmission of wave energy through a rubble-mound structure is relatively less for the small-scale model than for the prototype. Consequently, some adjustment in small-scale model rubble-mound structures is needed to ensure satisfactory reproduction of wave-reflection and wave-transmission characteristics. In past investigations (Dai and Jackson 1966; Brasfeild and Ball 1967) at ERDC, this adjustment was made by determining wave-energy transmission characteristics of the proposed structure in a two-dimensional model using a scale large enough to ensure negligible scale effects. A cross section then was developed for the small-scale, three-dimensional model that would provide essentially the same relative transmission and reflection of wave energy. Therefore, from previous findings for structures and wave conditions similar to those at Kaunakakai, it was determined that a close approximation of the correct wave-energy transmission and reflection characteristics could be obtained by increasing the size of the rock used in the 1:75-scale model to approximately one and one half times that required for geometric similitude. Thus, in constructing the rubble-mound structures in the Kaunakakai Harbor model, rock sizes were computed linearly by scale, then multiplied by 1.5 to determine the actual sizes to be used in the model.

Ideally, a quantitative, three-dimensional, movable-bed model investigation would best determine the impacts of proposed modifications with regard to sediment deposition in the vicinity of the causeway and harbor. However, this type of model investigation is difficult and expensive to conduct, and each area in which such an investigation is contemplated must be carefully analyzed. In view of the complexities involved in conducting movable-bed model studies and due to limited funds and time for the Kaunakakai Harbor project, the model was molded in cement mortar (fixed-bed), and a tracer material was obtained to qualitatively determine sediment patterns and subsequent deposits in the vicinity of the project.

Model and Appurtenances

The model reproduced approximately 2,010 m (6,600 ft) of the Molokai shoreline, the existing causeway and harbors, and bathymetry in the Pacific Ocean to an offshore depth of 18.3 m (60 ft) with a sloping transition to the wave generator pit elevation of -22.9 m (-75 ft). Included was the relatively flat, shallow reef that extended seaward about 975 m (3,200 ft). The total area reproduced in the model was approximately 1,450 sq m (15,640 sq ft), representing about 8.3 sq km (3.2 square miles) in the prototype. Vertical control for model construction was based on mean lower low water (mllw), and horizontal control was referenced to a local prototype grid system. A general view of the model is shown in Figure 4.

Model waves were reproduced by a 21.3-m-long (70-ft-long), electro-hydraulic, unidirectional spectral wave generator with a trapezoidal-shaped, vertical motion plunger. The wave generator utilized a hydraulic power supply. The vertical motion of the plunger was controlled by a computer-generated

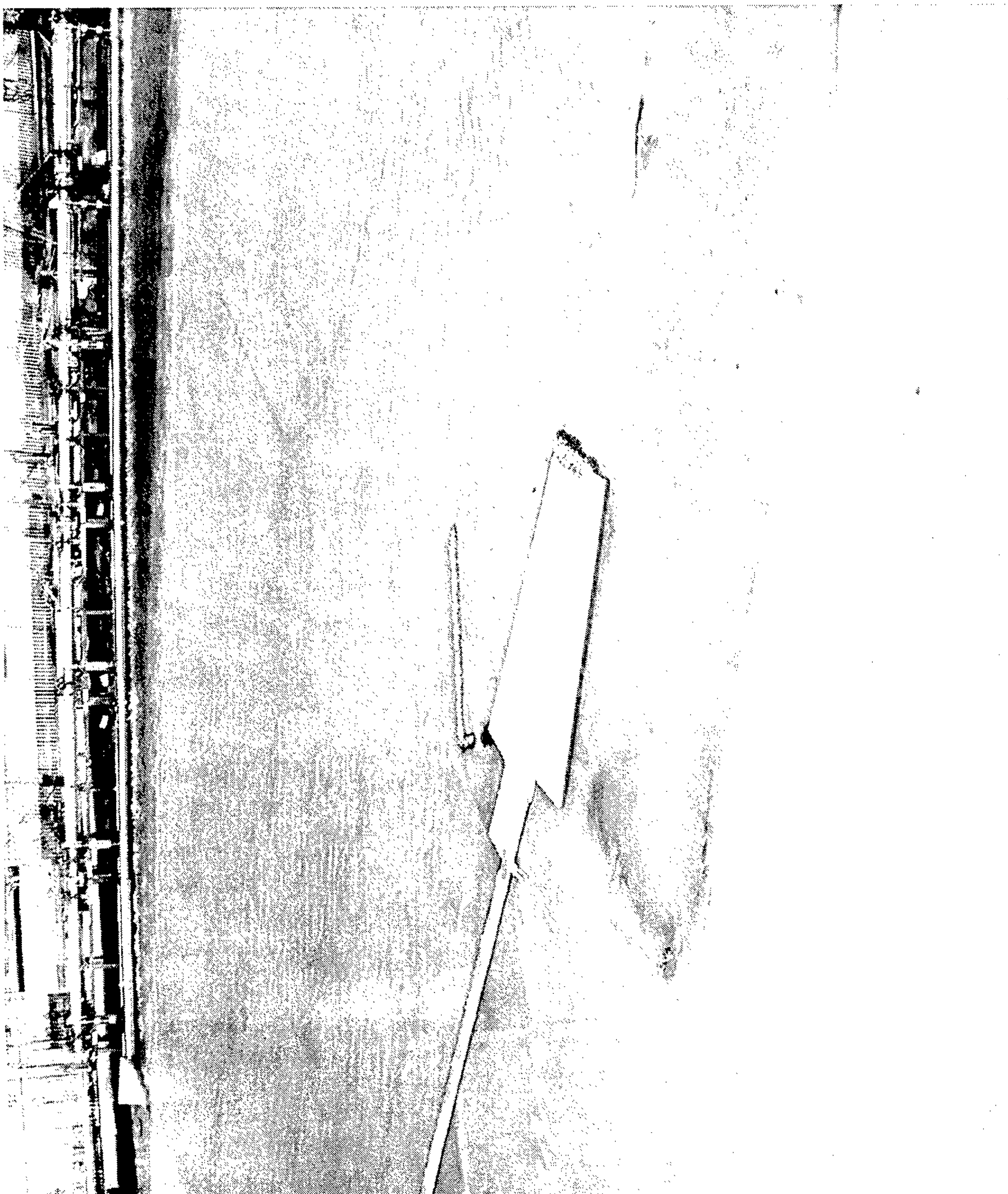

Figure 4. General view of model

command signal, and movement of the plunger caused a displacement of water which generated the required experimental waves. The wave generator also was mounted on retractable casters which enabled it to be positioned to generate waves from the required directions.

An automated data acquisition and control system, designed and constructed at ERDC (Figure 5), was used to generate and transmit wave generator control signals, monitor wave generator feedback, and secure and analyze wave data at selected locations in the model. Through the use of a microvax computer, the electrical output of parallel-wire, capacitance-type wave gauges, which varied with the change in water-surface elevation with respect to time, were recorded on magnetic disks. These data then were analyzed to obtain the parametric wave data.

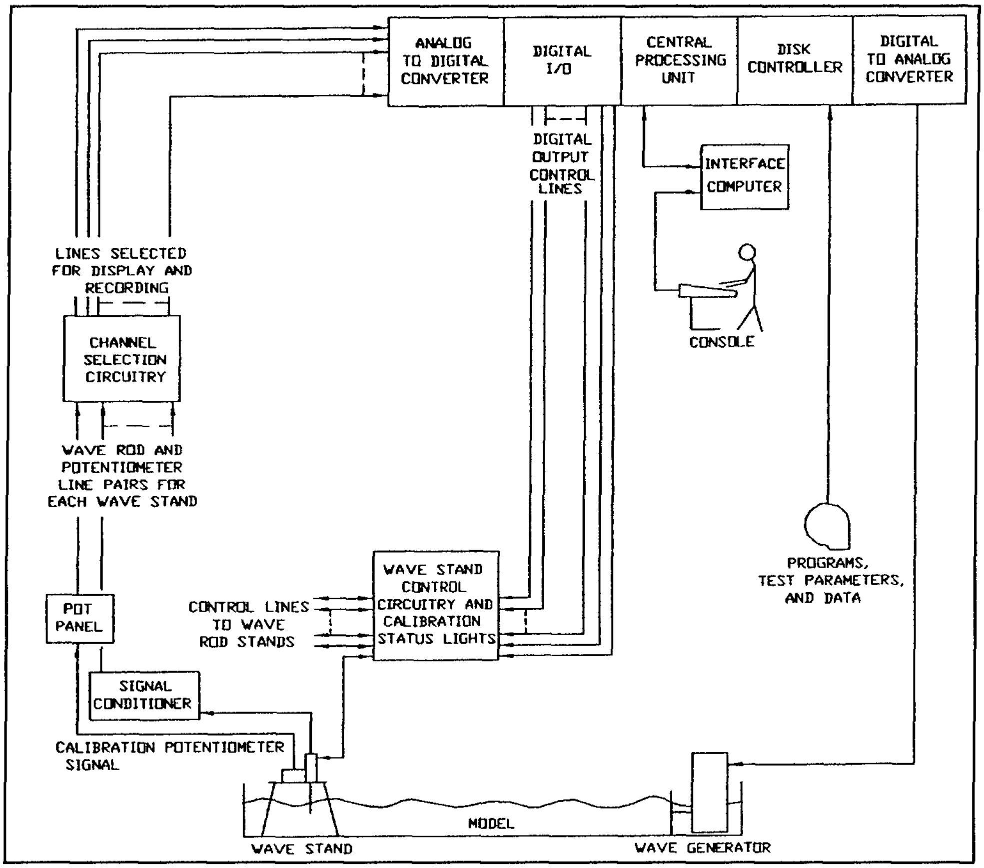

Figure 5. Automated data acquisition and control system

A 0.6-m (2-ft) (horizontal) solid layer of fiber wave absorber was placed along the inside perimeter of the model to dampen wave energy that might otherwise be reflected from the model walls. In addition, guide vanes were placed along the wave generator sides in the flat pit area to ensure proper formation of the wave train incident to the model contours.

Design of Tracer Material

As discussed previously, a fixed-bed model was constructed and a tracer material selected to qualitatively determine movement and deposition of sediment in the vicinity of the causeway and harbor. Tracer was chosen in accordance with the scaling relations of Noda (1972), which indicate a relation, or model law, among the four basic scale ratios, i.e., the horizontal scale, λ ; the vertical scale, μ; the sediment size ratio, η_D ; and the relative specific weight ratio, η_γ. These relations were determined experimentally using a wide range of wave conditions and bottom materials and are valid mainly for the breaker zone.

Noda's scaling relations indicate that movable-bed models with scales in the vicinity of 1:75 (model to prototype) should be distorted (i.e., they should have different horizontal and vertical scales). Since the fixed-bed model of Kaunakakai was undistorted to allow accurate reproduction of short-period wave and current patterns, the following procedure (which has been successfully used and validated for undistorted models) was used to select a tracer material. Using the prototype sand characteristics (median diameter, D_{50} = 0.54 mm, specific gravity = 2.71) and assuming the horizontal scale to be in similitude (i.e., 1:75), the median diameter for a given specific gravity of tracer material and the vertical scale were computed. The vertical scale was then assumed to be in similitude and the tracer median diameter and horizontal scale were computed. This resulted in a range of tracer sizes for given specific gravities that could be used. Although several types of movable-bed tracer materials were available at ERDC, previous investigations (Giles and Chatham 1974; Bottin and Chatham 1975) indicated that crushed coal tracer more nearly represented the movement of prototype sand. Therefore, quantities of crushed coal (specific gravity = 1.30; median diameter, D_{50} = 1.18 - 1.6 mm) were selected for use as a tracer material throughout the model investigation.

3 Experimental Conditions and Procedures

Selection of Experimental Conditions

Still-water level

Still-water levels (swl's) for wave action models are selected so that various wave-induced phenomena that are dependent on water depths are accurately reproduced in the model. These phenomena include refraction of waves in the project area, overtopping of harbor structures by waves, reflection of wave energy from various structures, and transmission of wave energy through porous structures.

In most cases, it is desirable to select a model swl that closely approximates the higher water stages which normally occur in the prototype for the following reasons:

a. The maximum amount of wave energy reaching a coastal area normally occurs during the higher water phase of the local tidal cycle.

b. Most storms moving onshore are characteristically accompanied by a higher water level due to wind, tide, and storm surge.

c. The selection of a high swl helps minimize model scale effects due to viscous bottom friction.

d. When a high swl is selected, a model investigation tends to yield more conservative results.

A swl of +0.64 m (+2.1 ft) were selected by the Honolulu District for use during the model experiments. This value represents mean higher high water (mhhw) and was used while obtaining wave heights, wave-induced current patterns and magnitudes, and sediment tracer patterns in the vicinity of the harbor and causeway.

Factors influencing selection of experimental wave characteristics

In planning the experimental program for a model investigation of harbor wave-action problems, it is necessary to select heights, periods, and directions for the experimental waves that will allow a realistic study of the proposed improvement plans and an accurate evaluation of the elements of the various proposals. Surface-wind waves are generated primarily by the interactions between tangential stresses of wind flowing over water, resonance between the water surface and atmospheric turbulence, and interactions between individual wave components. The height and period of the maximum significant wave that can be generated by a given storm depend on the wind speed, the length of time that wind of a given speed continues to blow, and the distance over water (fetch) that the wind blows. Selection of experimental wave conditions entails evaluation of such factors as:

a. Fetch and decay distances (the latter being the distance over which waves travel after leaving the generating area) for various directions from which waves can approach the problem area.

b. Frequency of occurrence and duration of winds from the different directions.

c. Alignment, size, and relative geographic position of the navigation structures.

d. Alignments, lengths, and locations of the various reflecting surfaces in the area.

e. Refraction of waves caused by differentials in depth in the area seaward of the site, which may create either a concentration or a diffusion of wave energy.

Selection of experimental waves

Measured prototype data covering a sufficiently long duration from which to base a comprehensive statistical analysis of wave conditions were unavailable for the Kaunakakai Harbor area. The wave-induced circulation and sedimentation problems at the site, however, were not considered to be caused by deepwater storm waves that may approach from various directions, but from locally generated wind waves coming predominantly from the easterly directions. Therefore, wind data were first examined and wave conditions developed from these data.

Two National Data Buoy Center (NDBC) buoys are located in the general vicinity of Molokai. They are Buoy 51026, located about 14.5 km (9 miles) north of Molokai, and Buoy 51027, situated approximately 56 km (35 miles) south of Molokai. Wind data, covering 1 year of measurements, were obtained from these buoys. Wind speed and direction data are summarized in Figures 6 and 7 for Buoys 51026 and 51027, respectively. Wind speeds up to 10 m/s (22 mph) were

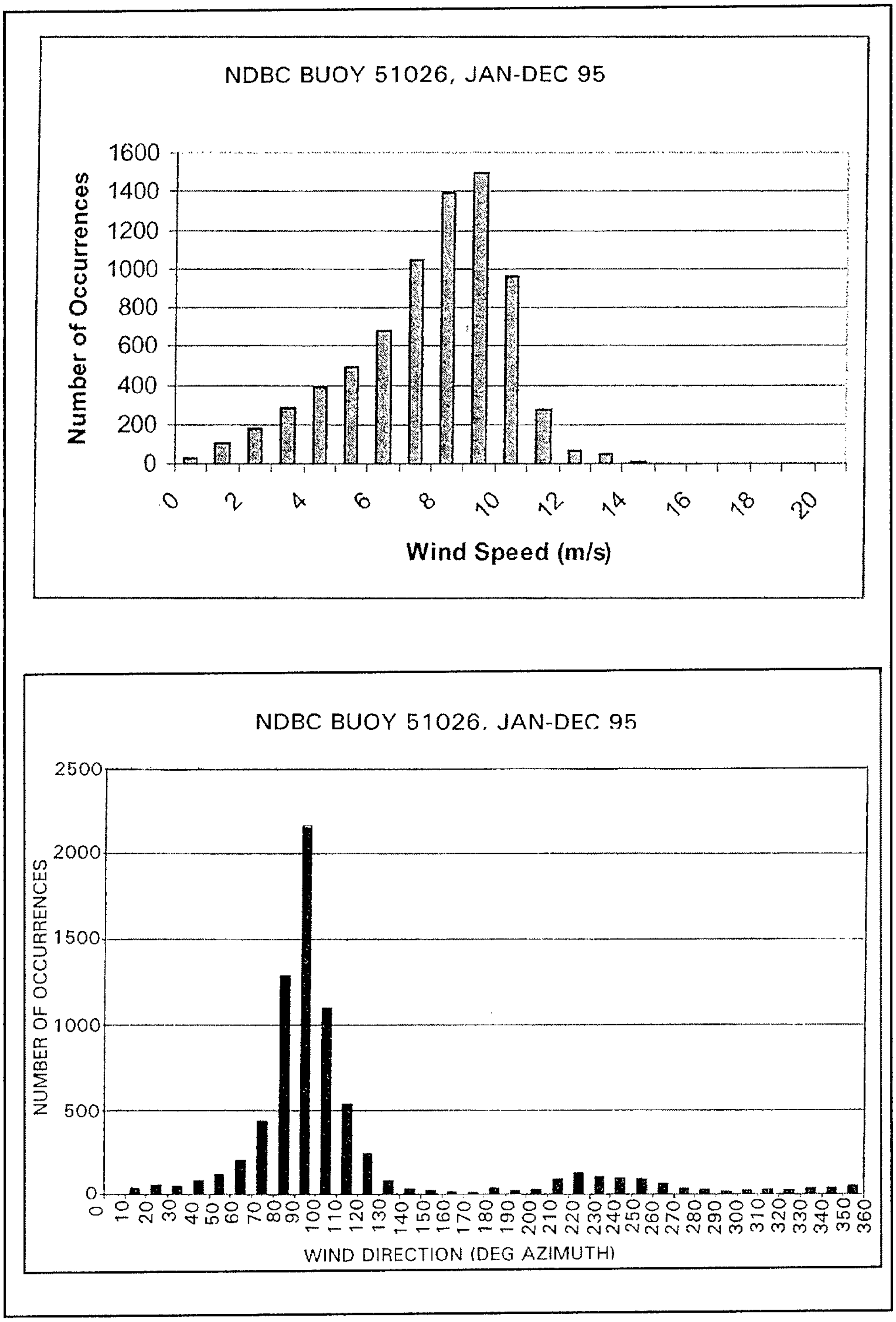

Figure 6. Wind speed and direction data obtained from NDBC Buoy 51026

common at both sites, with maximum winds of 15 m/s (34 mph) recorded at the northern buoy and 17 m/s (38 mph) at the southern one. The data indicate that winds approach predominantly from the easterly directions at both buoy locations. The majority of occurrences from the northern buoy relative to direction ranged

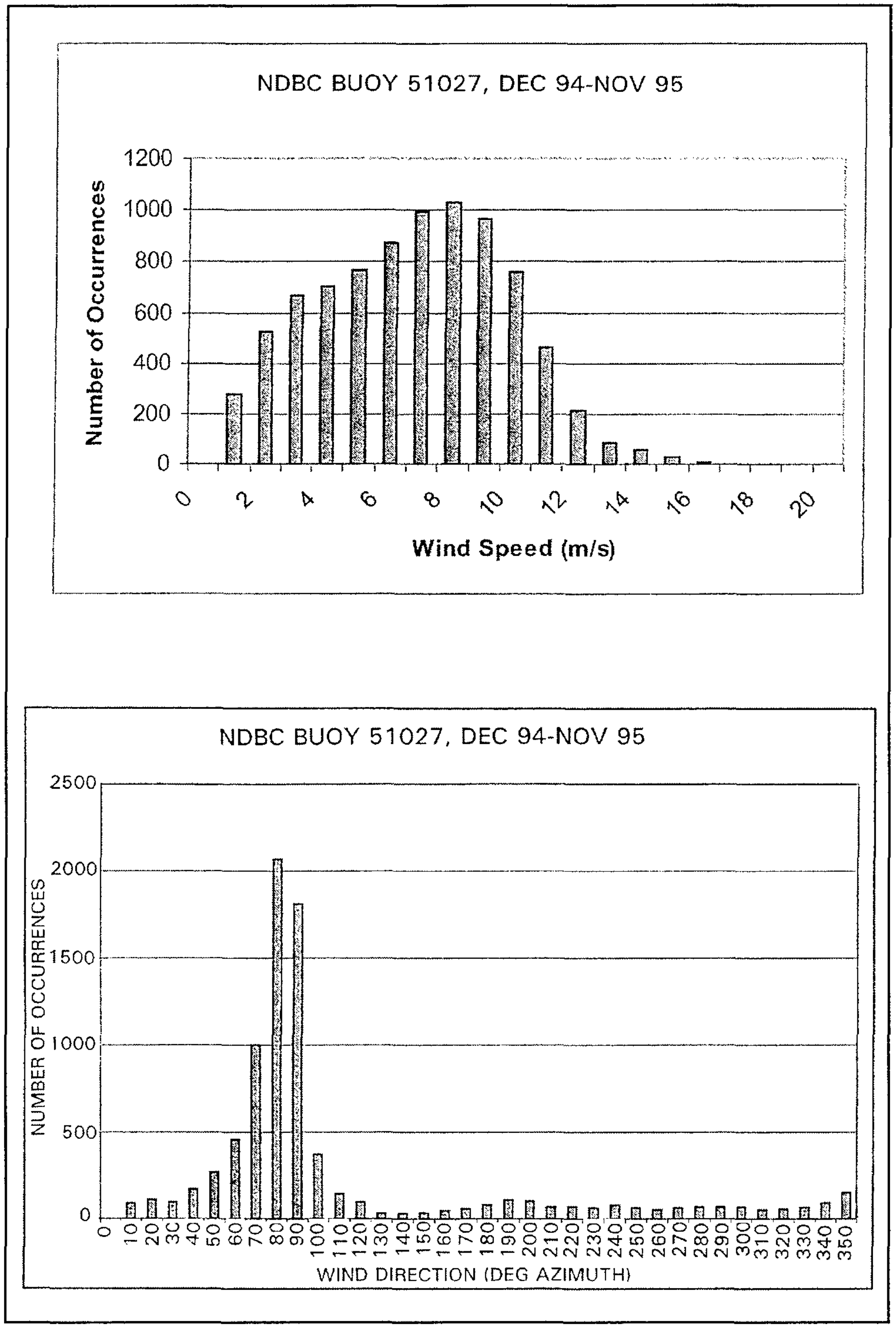

Figure 7. Wind speed and direction data obtained from NDBC Buoy 51027

from 90 to 110 deg, while those from the southern buoy ranged from 70 to 90 deg. These data support local observations (winds approaching from the easterly directions). Though not shown in the figures, the higher wind speeds occurred with the dominant easterly directions as opposed to an atypical direction.

Since buoy wind data are consistent with local observations relative to wind direction, it is expected that the buoy wind speeds also provide a reasonable representation of winds along the study area. The available fetch from the harbor toward the east is limited by the island of Maui, a distance of 40 km (25 miles). The available fetch over the shallow reef to the east extends a distance of about 19 km (12 mile), where the Molokai shoreline turns northeasterly. Since the appropriate fetch and water depth for local wave growth affecting Kaunakakai Harbor were not well understood, a range of possibilities was considered to determine probable wave conditions at the site. These include both the 19-km (12 mile) and 40-km (25-mile) fetch lengths and water depths that ranged from a minimum of 1.5 m (5 ft), which represent the depth over the reef at high water, to water depths in deep water. Estimated wave growth curves over constant depth were determined for these variables from Engineer Manual 1110-2-1414. Significant wave heights and peak periods that could be generated over the 19-km (12-mile) and 40-km (25-mile) fetches are presented in Figures 8 and 9, respectively. Two scenarios were used to determine wave conditions at Kaunakakai. First considered were wave conditions possible at the site due to wave growth over the shallow reef for the 19-km (12-mile) fetch distance. Next considered were wave conditions possible from deep water for the 40-km (25-mile) fetch length. It was expected that the waves from deep water would be larger and that they would break as they propagated over the reef and reform.

Data indicated that wind speeds of 10 m/s (22 mph) were common at both Buoys 51026 and 51027. With these wind speeds, 2.7-sec, 0.4-m (1.3-ft) waves were considered representative for the 19-km (12-mile) fetch over the shallow reef; and 4.7-sec, 1.2-m (4-ft) waves were considered representative conditions for the 40-km (25-mile) fetch over deep water. A wind speed of 16 m/s (36 mph) was an average value of the upper limits recorded at both buoys. Using this value, 3.2-sec, 0.55-m (1.8-ft) waves were considered representative for the 19-km (12-mile) fetch; and 5.7-sec, 2.1-m (7-ft) waves were considered representative conditions for the 40-km (25-mile) fetch length.

Based upon this rationale, the following experimental wave conditions were selected for use in the physical model:

Period, sec	Height, m (ft)
2.7	0.4 (1.3)
3.2	0.55 (1.8)
4.7	1.2 (4)
5.7	2.1 (7)

The range of predominant wind directions at Buoys 51026 and 51027 was from 70 to 110 deg with a high incidence of 90-deg wind directions for each buoy. Since the shoreline east of the causeway generally extends in an easterly direction, winds from 70 deg would blow slightly offshore. Therefore, based upon the shoreline orientation at the site, 90 and 110-deg wave directions were selected for use during model experiments.

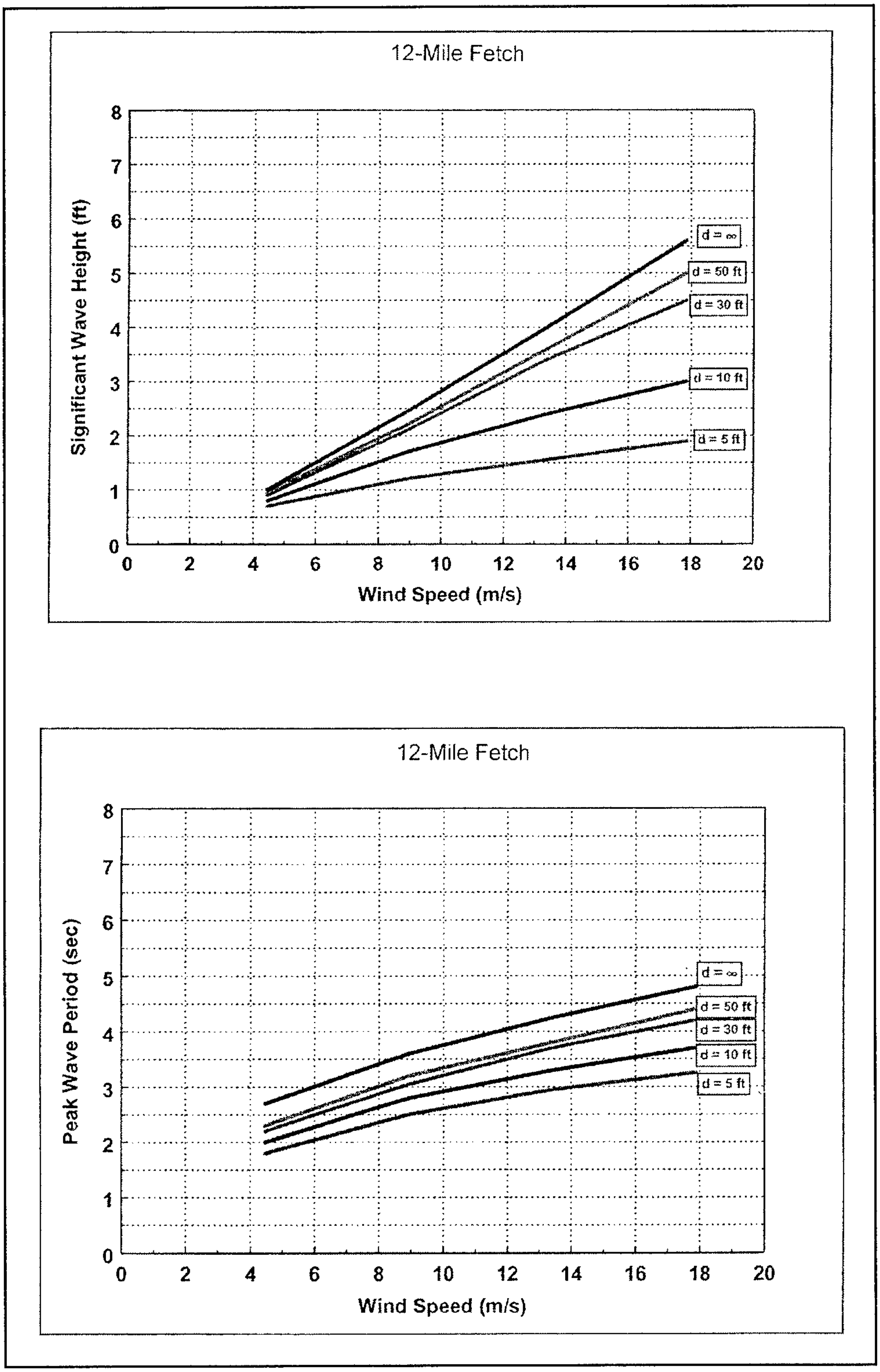

Figure 8. Significant wave height and peak wave period for 19-km (12-mile) fetch

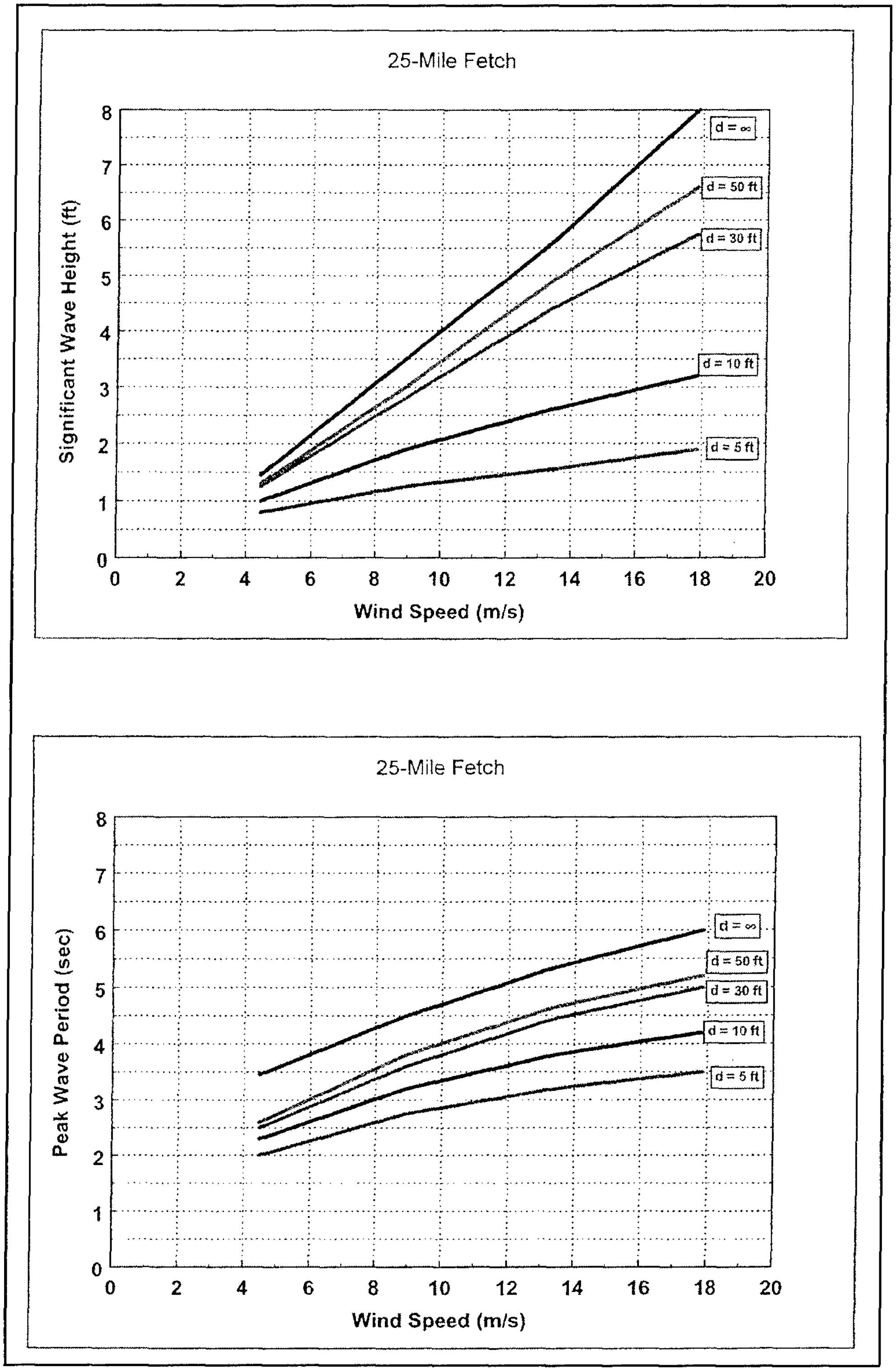

Figure 9. Significant wave height and peak wave period for 40-km (25-mile) fetch

Unidirectional wave spectra were generated based on Texel-MARSEN-ARSLOE (TMA) parameters initially for the selected waves for use in the model investigation. Plots of a typical wave spectra are shown in Figure 10. The dashed line represents the desired spectra, while the solid line represents the spectra reproduced in the model. A generic TMA gamma function of 3.3 was used to determine the spread of the spectra. The larger the gamma value, the sharper the peak in the energy-distribution curve. A typical wave train time series is shown in Figure 11, which depicts water-surface elevation versus time. Selected waves were defined as significant wave height, the average height of the highest one-third of the waves or H_s. In deep water, H_s is very similar to H_{mo} (energy based wave) where $H_{mo} = 4\,(E)^{1/2}$, and E equals total energy in the spectra, which is obtained by integrating the energy density spectra over the frequency range. After experiments were initiated, it was noted that the larger waves (1.2- and 2.1-m (4- and 7-ft waves) broke on the shallow reef, reformed, and propagated toward shore. The 0.4-m (1.3-ft) and 0.55-m (1.8-ft) waves at the wave generator were significantly reduced in the area immediately east of the causeway. To reproduce the desired wave heights in this area (east of the causeway), it was necessary to use monochromatic wave conditions. Therefore, the 0.4-m (1.3-ft) and 0.55-m (1.8-ft) waves generated in the model were monochromatic conditions and defined on the reef east of the causeway, and the 1.2-m (4-ft) and 2.1-m (7-ft) waves generated were spectral conditions and defined at the wave generator in deep water.

Analysis of Model Data

Relative merits of the various plans were evaluated by:

a. Comparison of wave heights at selected locations in the model.

b. Comparison of wave-induced current patterns and magnitudes.

c. Comparison of sediment tracer movement and subsequent deposits.

d. Visual observations and wave pattern photographs.

In the wave-height data analysis, the average height of the highest one-third of the waves (H_s), recorded at each gauge location, was computed. All wave heights then were adjusted by application of Keulegan's equation[1] to compensate for excessive model wave height attenuation due to viscous bottom friction. From this equation, reduction of model wave heights (relative to the prototype) can be calculated as a function of water depth, width of wave front, wave period, water viscosity, and distance of wave travel and the model data can be corrected and converted to their prototype equivalents.

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[1] G. H. Keulegan. (1950). "The gradual damping of a progressive oscillatory wave with distance in a prismatic rectangular channel," Unpublished data, National Bureau of Standards, Washington, DC, prepared at request of Director, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, by letter of 2 May 1950.

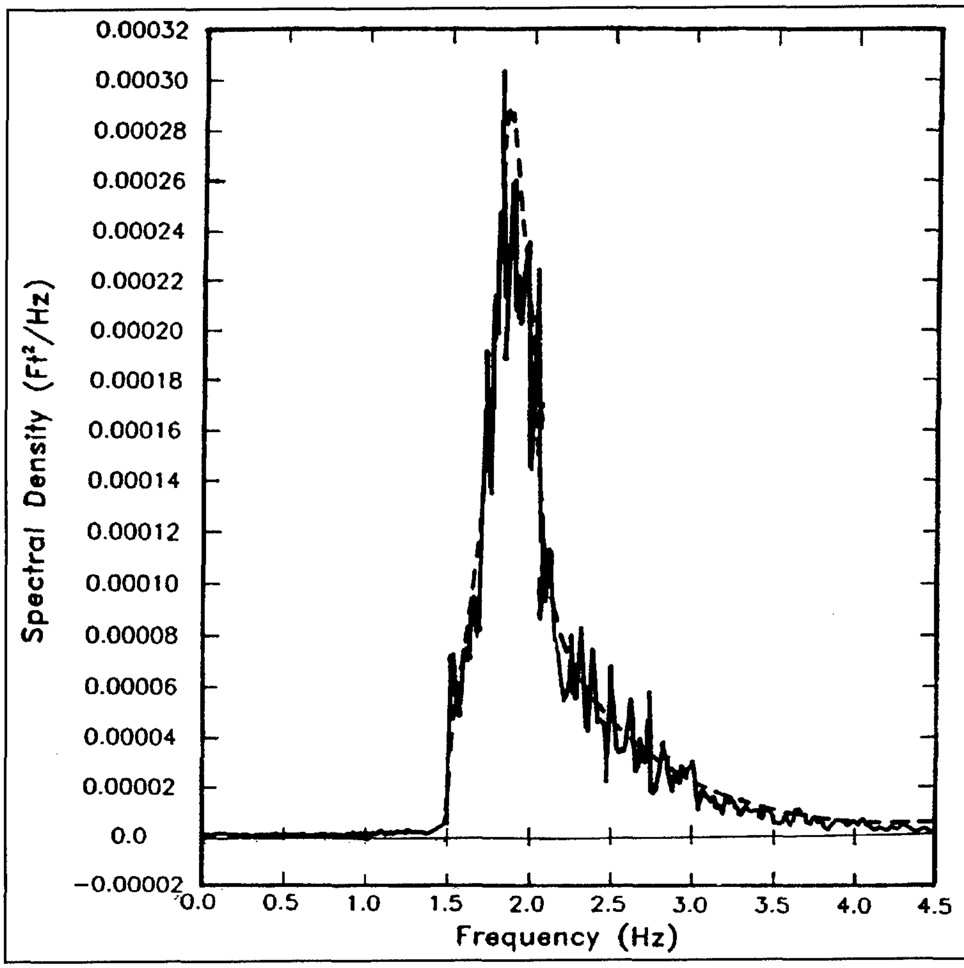

Figure 10. Typical energy density versus frequency plots (model terms) for a wave spectra; 4.7-sec, 1.4-m (4.0-ft) waves (prototype)

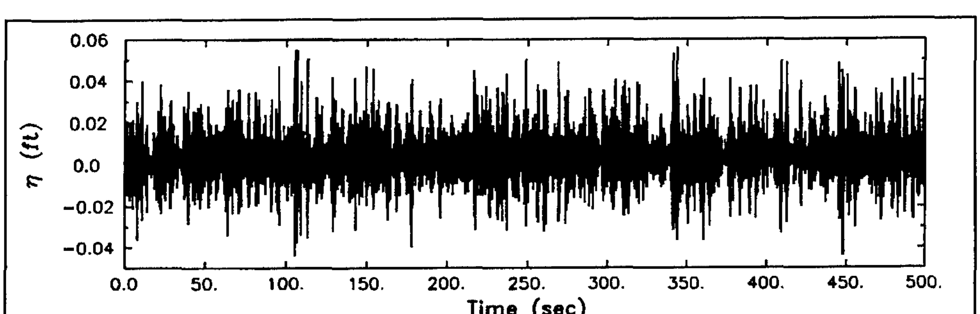

Figure 11. Typical model-scale wave train time series; 4.7-sec, 1.4-m (4.0-ft) waves (prototype)

4 Experiments and Results

Experiments

Existing conditions

Comprehensive experiments were conducted for existing conditons (Plate 1) to establish a base from which to evaluate the effectiveness of the various improvement plans. Wave height data were secured at various locations in the model. Wave-induced current patterns and magnitudes and wave pattern photographs were also obtained, and sediment tracer experiments were conducted for representative wave conditions.

Improvement plans

Wave heights, wave-induced current patterns and magnitudes, and/or wave pattern photographs were obtained for several improvment plans. All plans entailed the installation of a dredged basin east of and adjacent to the causeway. Some plans involved the installation of box culverts through the causeway to improve circulation, while others entailed larger breaches in areas where a pile-supported roadway, or a bridge, may be installed. Sediment tracer experiments were conducted for the most promising improvement plans. Brief descriptions of improvement plans are presented in the following subparagraphs, and dimensional details are shown in Plates 2-7.

a. Plan 1 (Plate 2) consisted of deepening the area immediately east of the causeway. Part of the area was deepened to a -0.6-m (-2-ft) depth, while another was dredged to -0.9 m (-3 ft). The plan also included the installation of three 6.1-m-wide (20-ft-wide) openings (representing box culverts) through the causeway. The most landward opening was located at the shoreline and the others were situated seaward every 171.5 m (562.5 ft).

b. Plan 2 (Plate 3) included the deepened area of Plan 1 east of the causeway, and six 6.1-m-wide (20-ft-wide) openings constructed through the causeway. The most landward opening was located at the shoreline and the others were located seaward every 57.2 m (187.5 ft).

c. Plan 3 (Plate 4) entailed the deepened area of Plan 1 east of the causeway, and nine 6.1-m-wide (20-ft-wide) openings constructed through the causeway. The most landward opening was situated at the shoreline and the others were located seaward every 57.2 m (187.5 ft).

d. Plan 4 (Plate 5) consisted of the deepened area of Plan 1 east of the causeway with a 122-m (400-ft) opening in the causeway extending from the shoreline in a seaward direction. The opening could represent a pile-supported causeway, or a bridge.

e. Plan 5 (Plate 6) involved the deepened area of Plan 1 east of the causeway with a 183-m (600-ft) opening in the causeway extending seaward from the shoreline. The opening represents a pile-supported causeway, or a bridge.

f. Plan 6 (Plate 7) included the deepened area east of the causeway of Plan 1 and the 600-ft opening in the causeway of Plan 5. In addition, the inner portion of the causeway from the shoreline up the existing slope shoreward was removed and the shoreline was restored to a more natural state in this area (i.e., the existing fillet adjacent to the causeway was removed).

Wave height experiments

Wave height experiments were conducted for existing conditions and the improvement plans for the selected experimental waves from at least one incident wave direction. The most promising plan was subjected to waves from both incident directions. Wave gauge locations are shown in referenced plates.

Wave-induced current patterns and magnitudes and wave patterns

Wave-induced current patterns and magnitudes and wave patterns were obtained for existing conditions and proposed improvement plans for experimental waves from at least one incident wave direction. The most promising plan was subjected to waves from both incident directions. These experiments were conducted by timing the progress of a dye tracer relative to a known distance on the model surface at selected locations in the model.

Sediment tracer experiments

Sediment tracer experiments were conducted for existing conditions and the most promising plans of improvement for representative experimental waves from the most critical incident direction. Sediment tracer was introduced into the model along the shoreline east of the causeway to determine sediment tracer patterns and subsequent deposition.

Experimental Results

In analyzing results, the relative merits of various improvement plans were based on wave-induced current patterns and magnitudes, measured wave heights, and the movement of sediment tracer material and deposition areas. Model wave heights (significant wave heights or H_s) were tabulated to show measured values at selected locations. Wave-induced current patterns and magnitudes are presented on plates, and sediment tracer patterns and subsequent deposits are depicted in photographs.

Existing conditions

Results of wave height experiments conducted for existing conditions for waves from 90 and 110 deg are presented in Table 1. For waves generated over the shallow reef from 90 deg with the 19-km (12-mile) fetch, maximum wave heights[1] were 0.3 m (1.0 ft) in the small-boat harbor (Gauge 3) and 0.18 m (0.6 ft) in the deep-draft port (Gauge 6). For waves generated in deep water from 90 deg with the 40-km (25-mile) fetch, maximum wave heights obtained were 0.46 m (1.5 ft) in the small-boat harbor and 0.24 m (0.8 ft) in the deep-draft port. Maximum wave heights in the small-boat harbor and deep-draft port for waves from 110 deg were 0.27 and 0.18 m (0.9 and 0.6 ft), respectively, for waves generated from over the shallow reef with the 19-km (12-mile) fetch; and 0.43 and 0.27 m (1.4 and 0.9 ft), respectively, for waves generated in deep water with the 40-km (25-mile) fetch. Visual observations revealed that the larger incident waves generated in deep water broke on the reef and expended their energy. This resulted in smaller wave height values east of the causeway (Gauge 1) than for the smaller incident waves representative of those generated over the shallow reef. Typical wave patterns obtained for existing conditions are shown in Photos 1-8.

Table 1
Wave Heights for Existing Conditions

Wave Condition			Wave Height at Indicated Gauge Location, m (ft)					
Direction (az)	Period (sec)	Height m (ft)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
90	2.7	0.4 (1.3)	0.43 (1.4)	0.15 (0.5)	0.18 (0.6)	0.03 (0.1)	0.15 (0.5)	0.18 (0.6)
	3.2	0.55 (1.8)	0.55 (1.8)	0.24 (0.8)	0.30 (1.0)	0.06 (0.2)	0.15 (0.5)	0.18 (0.6)
	4.7	1.2 (4)	0.27 (0.9)	0.30 (1.0)	0.30 (1.0)	0.03 (0.1)	0.15 (0.5)	0.18 (0.6)
	5.7	2.1 (7)	0.43 (1.4)	0.40 (1.3)	0.46 (1.5)	0.09 (0.3)	0.21 (0.7)	0.24 (0.8)
110	2.7	0.4 (1.3)	0.37 (1.2)	0.18 (0.6)	0.21 (0.7)	0.03 (0.1)	0.15 (0.5)	0.18 (0.6)
	3.2	0.55 (1.8)	0.46 (1.5)	0.21 (0.7)	0.27 (0.9)	0.06 (0.2)	0.09 (0.3)	0.18 (0.6)
	4.7	1.2 (4)	0.18 (0.6)	0.18 (0.6)	0.27 (0.9)	0.03 (0.1)	0.06 (0.2)	0.12 (0.4)
	5.7	2.1 (7)	0.34 (1.1)	0.30 (1.0)	0.43 (1.4)	0.06 (0.2)	0.21 (0.7)	0.27 (0.9)

[1] Refers to maximum significant wave heights throughout report.

Wave-induced current patterns and magnitudes obtained for existing conditions are shown in Plates 8-15 for waves from 90 and 110 deg. Currents generally moved westerly along the shoreline and then seaward parallel to the causeway. Some moved through the gap in the small-boat harbor breakwater, and some moved seaward east of the breakwater. Essentially no current movement was observed west of the causeway. Current patterns were similar for all wave conditions (i.e., illustrated in Photo 9), however, magnitudes differed for various conditions. For waves from 90 deg, maximum velocities ranged from 0.12 to 0.79 m/s (0.4 to 2.6 fps) along the shoreline east of the causeway; 0.24 to 1.2 m/s (0.8 to 4.1 fps) in the area adjacent to the causeway; 0.43 to 2.04 m/s (1.4 to 6.7 fps) in the breakwater gap; 0.18 to 1.55 m/s (0.6 to 5.1 fps) through the small-boat harbor; and 0.18 to 1.19 m/s (0.6 to 3.9 fps) in the area east of the breakwater. For waves from 110 deg, maximum velocities ranged from 0.3 to 0.88 m/s (1.0 to 2.9 fps) along the shoreline east of the causeway; 0.27 to 1.1 m/s (0.9 to 3.6 fps) in the area adjacent to the causeway; 0.21 to 2.19 m/s (0.7 to 7.2 fps) in the breakwater gap; 0.24 to 0.85 m/s (0.8 to 2.8 fps) through the small-boat harbor; and 0.18 to 1.25 m/s (0.6 to 4.1 fps) in the area east of the breakwater. It was noted that the smaller incident wave conditions generated over the shallow reef for the smaller fetch, in general, resulted in greater velocities in the vicinity of the causeway than the larger incident waves generated in deep water with the longer fetch.

The general movement of sediment tracer material and subsequent deposits for existing conditions are shown in Photo 10. Sediment was introduced into the model along the shoreline east of the causeway. The experiments entailed exposing the tracer material to 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg for a 40-hr (model time) duration. Sediment tracer material slowly migrated westerly along the shoreline and then southwesterly (seaward) along the causeway resulting in deposits in these areas.

Improvement plans

Wave heights obtained for Plan 1 for waves from 90 deg are presented in Table 2. For waves generated over the shallow reef with the 19-km (12-mile) fetch, maximum wave heights were 0.3 m (1.0 ft) in the small-boat harbor (Gauge 3) and 0.18 m (0.6 ft) in the deep-draft port (Gauge 6). For wave conditions generated in deep water with the 40-km (25-mile) fetch, maximum heights were 0.4 m (1.3 ft) in the small-boat harbor and 0.18 m (0.6 ft) in the deep-draft port. Typical wave patterns obtained for Plan 1 are presented in Photos 11-14.

Wave-induced current patterns and magnitudes obtained for Plan 1 are presented in Plates 16-19 for waves from 90 deg. Currents east of the causeway generally moved westerly along the shoreline and then seaward parallel to the causeway. Some moved through the gap in the small-boat harbor breakwater, and some moved seaward east of the breakwater. Currents also moved westerly through the culverts installed in the causeway. In general, these currents jetted through the culverts at relatively high velocities, meandered in eddies, and eventually dissipated. Typical current patterns are shown in Photo 15. For

Table 2
Wave Heights for Plan 1 for Waves from 90 Degrees

Wave Condition		Wave Heights at Indicated Gauge Location, m (ft)					
Period (sec)	Height m (ft)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
2.7	0.4 (1.3)	0.46 (1.5)	0.09 (0.3)	0.15 (0.5)	0.03 (0.1)	0.09 (0.3)	0.18 (0.5)
3.2	0.55 (1.8)	0.55 (1.8)	0.24 (0.8)	0.30 (1.0)	0.06 (0.2)	0.15 (0.5)	0.18 (0.6)
4.7	1.2 (4)	0.24 (0.8)	0.21 (0.7)	0.21 (0.7)	0.06 (0.2)	0.09 (0.3)	0.12 (0.4)
5.7	2.1 (7)	0.40 (1.3)	0.30 (1.0)	0.40 (1.3)	0.09 (0.3)	0.15 (0.5)	0.18 (0.6)

various wave conditions, maximum velocities east of the causeway ranged from 0.24 to 0.85 m/s (0.8 to 2.8 fps) along the shoreline; 0.4 to 0.94 m/s (1.3 to 3.1 fps) in the area adjacent to the causeway; 0.24 to 2.07 m/s (0.8 to 6.8 fps) in the gap in the breakwater; 0.18 to 0.94 m/s (0.6 to 3.1 fps) through the small-boat harbor; and 0.4 to 1.55 m/s (1.3 to 5.1 fps) in the area east of the breakwater. Maximum velocities through the culverts ranged from 0.64 to 2.93 m/s (2.1 to 9.6 fps) and those west of the causeway ranged from 0.21 to 0.79 m/s (0.7 to 2.6 fps).

Wave heights obtained for Plan 2 are presented in Table 3 for waves from 90 deg. For waves generated from over the reef for the 19-km (12-mile) fetch, maximum wave heights were 0.24 m (0.8 ft) in the small-boat harbor (Gauge 3) and 0.18 m (0.6 ft) in the deep-draft port (Gauge 6). For waves generated in deep water for the 40-km (25-mile) fetch, maximum wave heights were 0.43 m (1.4 ft) in the small-boat harbor and 0.24 m (0.8 ft) in the deep-draft port. Typical wave patterns obtained for Plan 2 are shown in Photos 16-19.

Table 3
Wave Heights for Plan 2 for Waves from 90 Degrees

Wave Condition		Wave Heights at Indicated Gauge Location, m (ft)					
Period (sec)	Height m (ft)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
2.7	0.4 (1.3)	0.43 (1.4)	0.18 (0.6)	0.21 (0.7)	0.06 (0.2)	0.15 (0.5)	0.18 (0.6)
3.2	0.55 (1.8)	0.55 (1.8)	0.21 (0.7)	0.24 (0.8)	0.06 (0.2)	0.15 (0.5)	0.15 (0.5)
4.7	1.2 (4)	0.34 (1.1)	0.27 (0.9)	0.30 (1.0)	0.06 (0.2)	0.12 (0.4)	0.18 (0.6)
5.7	2.1 (7)	0.49 (1.6)	0.34 (1.1)	0.43 (1.4)	0.12 (0.4)	0.18 (0.6)	0.24 (0.8)

Wave-induced current patterns and magnitudes obtained for Plan 2 are presented in Plates 20-23 for waves from 90 deg. Currents east of the causeway generally moved westerly along the shoreline and then seaward parallel to the causeway. Some moved through the gap in the small-boat harbor breakwater, and some moved seaward east of the breakwater. Currents also moved westerly through the culverts installed in the causeway. In general, these currents jetted through the culverts at relatively high velocities, meandered in eddies, and slowly

moved westerly. Typical current patterns are shown in Photo 20. For various wave conditions, maximum velocities east of the causeway ranged from 0.30 to 1.00 m/s (1.0 to 3.3 fps) along the shoreline; 0.37 to 0.73 m/s (1.2 to 2.4 fps) in the area adjacent to the causeway; 0.46 to 1.65 m/s (1.5 to 5.4 fps) in the gap in the small-boat harbor breakwater; 0.18 to 1.19 m/s (0.6 to 3.9 fps) through the small-boat harbor; and 0.58 to 1.68 m/s (1.9 to 5.5 fps) in the area east of the breakwater. Maximum velocities through the culverts ranged from 1.31 to 3.11 m/s (4.3 to 10.2 fps) and those west of the causeway ranged from 0.09 to 0.70 m/s (0.3 to 2.3 fps).

Wave heights obtained for Plan 3 are presented in Table 4 for waves from 90 deg. For waves generated over the reef for the 19-km (12-mile) fetch, maximum wave heights were 0.3 m (1.0 ft) in the small-boat harbor (Gauge 3) and 0.18 m (0.6 ft) in the deep-draft port (Gauge 6). For waves generated in deep water for the 40-km (25-mile) fetch, maximum heights were 0.4 m (1.3 ft) in the small-boat harbor and 0.24 m (0.8 ft) in the deep-draft port. Typical wave patterns obtained for Plan 3 are presented in Photos 21-24.

Table 4
Wave Heights for Plan 3 for Waves from 90 Degrees

Wave Condition		Wave Heights at Indicated Gauge Location, m (ft)					
Period (sec)	Height m (ft)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
2.7	0.4 (1.3)	0.43 (1.4)	0.15 (0.5)	0.21 (0.7)	0.06 (0.2)	0.15 (0.5)	0.18 (0.6)
3.2	0.55 (1.8)	0.55 (1.8)	0.21 (0.7)	0.30 (1.0)	0.06 (0.2)	0.15 (0.5)	0.15 (0.5)
4.7	1.2 (4)	0.30 (1.0)	0.24 (0.8)	0.27 (0.9)	0.06 (0.2)	0.12 (0.4)	0.15 (0.5)
5.7	2.1 (7)	0.43 (1.4)	0.34 (1.1)	0.40 (1.3)	0.12 (0.4)	0.21 (0.7)	0.24 (0.8)

Wave-induced current patterns and magnitudes obtained for Plan 3 are presented in Plates 24-27 for waves from 90 deg. Currents east of the causeway generally moved westerly along the shoreline and then seaward parallel to the causeway. Some moved through the gap in the small-boat harbor breakwater, and some moved seaward east of the breakwater. Currents also moved westerly through the culverts installed in the causeway. In general, these currents jetted through the culverts at relatively high velocities, meandered in eddies, and slowly moved westerly. Typical current patterns are shown in Photo 25. For various wave conditions, maximum velocities east of the causeway ranged from 0.27 to 0.98 m/s (0.9 to 3.2 fps) along the shoreline; 0.34 to 0.73 m/s (1.1 to 2.4 fps) in the area adjacent to the causeway; 0.55 to 2.16 m/s (1.8 to 7.1 fps) in the gap in the small-boat harbor breakwater; 0.21 to 1.13 m/s (0.7 to 3.7 fps) through the small-boat harbor; and 0.61 to 1.43 m/s (2.0 to 4.7 fps) in the area east of the breakwater. Maximum velocities through the culverts ranged from 1.46 to 3.38 m/s (4.8 to 11.1 fps) and those west of the causeway ranged from 0.15 to 0.79 m/s (0.5 to 2.6 fps).

After evaluation of current patterns and magnitudes obtained for Plans 1-3, Plan 2 was selected for sediment tracer experiments. The general movement of

tracer material and subsequent deposits are shown in Photo 26. Sediment tracer material east of the causeway migrated westerly along the shoreline and moved through the most shoreward culvert. It subsequently deposited in an area west of the causeway.

Wave heights obtained for Plan 4 for waves from 90 deg are presented in Table 5. For waves generated over the reef for the 19-km (12-mile) fetch, maximum wave heights were 0.24 m (0.8 ft) in the small-boat harbor (Gauge 3) and 0.15 m (0.5 ft) in the deep-draft port (Gauge 6). For waves generated in deep water for the 40-km (25-mile) fetch, maximum wave heights were 0.4 m (1.3 ft) in the small-boat harbor and 0.21 m (0.7 ft) in the deep-draft port. Typical wave patterns for Plan 4 are shown in Photos 27-30.

Table 5
Wave Heights for Plan 4 for Waves from 90 Degrees

Wave Condition		Wave Heights at Indicated Gauge Location, m (ft)					
Period (sec)	Height m (ft)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
2.7	0.4 (1.3)	0.52 (1.7)	0.15 (0.5)	0.21 (0.7)	0.09 (0.3)	0.12 (0.4)	0.15 (0.5)
3.2	0.55 (1.8)	0.58 (1.9)	0.18 (0.6)	0.24 (0.8)	0.15 (0.5)	0.15 (0.5)	0.15 (0.5)
4.7	1.2 (4)	0.27 (0.9)	0.15 (0.5)	0.21 (0.7)	0.09 (0.3)	0.12 (0.4)	0.12 (0.4)
5.7	2.1 (7)	0.40 (1.3)	0.24 (0.8)	0.40 (1.3)	0.12 (0.4)	0.18 (0.6)	0.21 (0.7)

Wave-induced current patterns and magnitudes obtained for Plan 4 are presented in Plates 28-31 for waves from 90 deg. Currents east of the causeway generally moved westerly along the shoreline and then seaward parallel to the outer portion of the causeway. Some moved through the gap in the small-boat harbor breakwater, and some moved seaward east of the breakwater. Currents also moved westerly through the 122-m (400-ft) opening in the causeway. For various wave conditions, maximum velocities east of the causeway ranged from 0.49 to 1.04 m/s (1.6 to 3.4 fps) along the shoreline; 0.18 to 0.79 m/s (0.6 to 2.6 fps) in the area adjacent to the causeway; 0.91 to 2.32 m/s (3.0 to 7.6 fps) in the gap in the small-boat breakwater; 0.27 to 1.49 m/s (0.9 to 4.9 fps) through the small-boat harbor; and 0.37 to 1.55 m/s (1.2 to 5.1 fps) in the area east of the breakwater. Maximum velocities through the opening in the causeway ranged from 0.76 to 2.29 m/s (2.5 to 7.5 fps) and those west of the causeway ranged from 0.73 to 1.89 m/s (2.4 to 6.2 fps). Typical current patterns for Plan 4 are shown in Photo 31.

Results of wave height experiments conducted for Plan 5 for waves from 90 and 110 deg are presented in Table 6. For waves from 90 deg generated over the shallow reef for the 19-km (12-mile) fetch, maximum wave heights were 0.21 m (0.7 ft) in the small-boat harbor (Gauge 3) and 0.15 m (0.5 ft) in the deep-draft port (Gauge 6). For waves from 90 deg generated in deep water for the 40-km (25-mile) fetch, maximum wave heights obtained were 0.4 m (1.3 ft) in the small-boat harbor and 0.24 m (0.8 ft) in the deep-draft port. Maximum wave heights in the small-boat harbor and deep-draft port for waves from 110 deg were 0.21 and

Table 6 Wave Heights for Plan 5								
Wave Condition			Wave Height at Indicated Gauge Location, m (ft)					
Direction (az)	Period (sec)	Height m (ft)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
90	2.7	0.4 (1.3)	0.43 (1.4)	0.12 (0.4)	0.12 (0.4)	0.12 (0.4)	0.12 (0.4)	0.15 (0.5)
	3.2	0.55 (1.8)	0.52 (1.7)	0.18 (0.6)	0.21 (0.7)	0.18 (0.6)	0.12 (0.4)	0.15 (0.5)
	4.7	1.2 (4)	0.21 (0.7)	0.15 (0.5)	0.21 (0.7)	0.06 (0.2)	0.09 (0.3)	0.12 (0.4)
	5.7	2.1 (7)	0.40 (1.3)	0.30 (1.0)	0.40 (1.3)	0.12 (0.4)	0.18 (0.6)	0.24 (0.8)
110	2.7	0.4 (1.3)	0.40 (1.3)	0.12 (0.4)	0.18 (0.6)	0.15 (0.5)	0.12 (0.4)	0.18 (0.6)
	3.2	0.55 (1.8)	0.55 (1.8)	0.15 (0.5)	0.21 (0.7)	0.24 (0.8)	0.09 (0.3)	0.18 (0.6)
	4.7	1.2 (4)	0.24 (0.8)	0.12 (0.4)	0.24 (0.8)	0.06 (0.2)	0.09 (0.3)	0.15 (0.5)
	5.7	2.1 (7)	0.40 (1.3)	0.24 (0.8)	0.37 (1.2)	0.12 (0.4)	0.18 (0.6)	0.24 (0.8)

0.18 m (0.7 and 0.6 ft), respectively, for waves generated for the 19-km (12-mile) fetch; and 0.37 and 0.24 m (1.2 and 0.8 ft), respectively, for waves generated from the 40-km (25-mile) fetch. Typical wave patterns for Plan 5 are presented in Photos 32-39.

Wave-induced current patterns and magnitudes obtained for Plan 5 are shown in Plates 32-39 for waves from 90 and 110 deg. Currents east of the causeway generally moved westerly along the shoreline and then seaward parallel to the outer portion of the causeway. Some moved through the gap in the small-boat breakwater, and some moved seaward easterly of the breakwater. Currents also moved westerly through the 183-m (600-ft) opening in the causeway. For waves from 90 deg, maximum velocities east of the causeway ranged from 0.37 to 1.07 m/s (1.2 to 3.5 fps) along the shoreline; 0.18 to 0.61 m/s (0.6 to 2.0 fps) in the area adjacent to the causeway; 0.64 to 1.95 m/s (2.1 to 6.4 fps) in the gap in the breakwater; 0.12 to 1.43 m/s (0.4 to 4.7 fps) through the small-boat harbor; and 0.52 to 1.34 m/s (1.7 to 4.4 fps) in the area east of the breakwater. Maximum velocities through the opening in the causeway ranged from 0.67 to 2.04 m/s (2.2 to 6.7 fps) and those west of the causeway ranged from 0.67 to 1.92 m/s (2.2 to 6.3 fps). For waves from 110 deg, maximum velocities east of the causeway ranged from 0.46 to 1.22 m/s (1.5 to 4.0 fps) along the shoreline; 0.24 to 0.61 m/s (0.8 to 2.0 fps) in the area adjacent to the causeway; 0.55 to 2.23 m/s (1.8 to 7.3 fps) in the breakwater gap; 0.34 to 1.10 m/s (1.1 to 3.6 fps) through the small-boat harbor; and 0.55 to 1.71 m/s (1.8 to 5.6 fps) in the area east of the breakwater. Maximum velocities through the opening in the causeway ranged from 0.70 to 2.32 m/s (2.3 to 7.6 fps), and those west of the causeway ranged from 0.64 to 2.19 m/s (2.1 to 7.2 fps) Typical current patterns for Plan 5 are shown in Photo 40.

After evaluation of current patterns and magnitudes obtained for Plans 4 and 5, sediment tracer experiments were conducted for Plan 5. The general movement

of tracer material and subsequent deposits are shown in Photo 41 for Plan 5. Sediment tracer material east of the causeway migrated westerly along the shoreline, around the inner portion of the causeway through the opening, and continued moving westerly.

The inner portion of the causeway for Plan 5 (Photo 42) was removed and the shoreline was restored to a more natural slope (Plan 6, Photo 43) to eliminate undesirable eddies observed west of the structure. Wave-induced current patterns and magnitudes obtained for Plan 6 for waves from 90 deg are presented in Plates 40-43. Currents east of the causeway moved westerly along the shoreline and then seaward parallel to the outer portion of the causeway. Some moved through the gap in the small-boat harbor breakwater, and some moved seaward east of the breakwater. Currents also moved through the opening in the causeway and westerly downcoast. For various wave conditions, maximum velocities east of the causeway ranged from 0.49 to 1.28 m/s (1.6 to 4.2 fps) along the shoreline; 0.12 to 0.61 m/s (0.4 to 2.0 fps) in the area adjacent to the causeway; 0.76 to 2.04 m/s (2.5 to 6.7 fps) in the gap in the small-boat harbor breakwater; 0.18 to 1.16 m/s (0.6 to 3.8 fps) through the small-boat harbor; and 0.43 to 1.37 m/s (1.4 to 4.5 fps) in the area east of the breakwater. Maximum velocities through the opening in the causeway ranged from 0.58 to 1.77 m/s (1.9 to 5.8 fps) and those west of the causeway ranged from 0.64 to 1.92 m/s (2.1 to 6.3 fps). Typical current patterns are shown in Photo 44 for Plan 6.

The general movement of tracer material and subsequent deposits are shown in Photo 45 for Plan 6. Sediment tracer material east of the causeway migrated westerly along the shoreline, through the opening in the causeway, and continued moving in a westerly direction downcoast.

Discussion of experimental results

Results of wave height experiments for existing conditions indicated that wave heights up to 0.46 m (1.5 ft) would occur in the small-boat harbor east of Pier Island with wave heights of 0.27 m (0.9 ft) in the deep-draft port west of the island. These values occurred for storm waves generated deep water for the 40-km (25-mile) fetch. It was noted that these waves (approaching from deep water) broke on the edge of the reef and expended their energy. Thus, wave heights east of the causeway (shoreward of Pier Island) were less for the 1.2- to 2.1-m (4- to 7-ft) incident wave conditions for the 40-km (25-mile) fetch than for the smaller 0.4 to 0.55 m (1.3 to 1.8 ft) locally-generated incident wave conditions due to wave growth over the shallow reef for the 19-km (12-mile) fetch.

Wave-induced current patterns obtained for existing conditions indicated westerly current movement along the shoreline and then seaward movement parallel to the causeway. Some then moved through the gap in the small-boat harbor breakwater and some moved seaward east of the breakwater. Current magnitudes of over 1.22 m/s (4.0 fps) along the causeway and 2.13 m/s (7.0 fps) through the breakwater gap were noted. Incident waves for the 19-km (12-mile) fetch resulted in greater velocities than the larger incident waves for the 40-km (25-mile) fetch.

Results of qualitative sediment tracer experiments for existing conditions indicated that sediment in the reef area east of the causeway will move westerly along the shoreline and then seaward adjacent to the causeway and result in deposits in these areas. Deposits observed in the model were similar to those observed in the prototype at low tide conditions during a site visit conducted in September 1999.

An examination of wave height data obtained for the improvement plans indicated that wave heights in the small-boat harbor and deep-draft port were similar for all plans. Depending on the plan, maximum wave heights in the small-boat harbor ranged from 0.4 to 0.43 m (1.3 to 1.4 ft) and from 0.18 to 0.24 m (0.6 to 0.8 ft) in the deep-draft port. When compared to wave heights obtained for existing conditions, values were either slightly less for the improvement plans (by 0.03 to 0.06 m (0.1 to 0.2 ft)); or the values were identical. These results indicate that none of the proposed improvement plans studied will have any adverse impacts on wave conditions in the existing small-boat harbor or deep-draft port.

Examination of wave-induced current patterns and magnitudes for the causeway culvert plans (Plans 1-3) revealed that current patterns east of the causeway were similar to existing conditions. For all the culvert plans, however, currents jettied through the culverts, meandered in eddies, and dissipated or only slowly migrated westerly. The three-culvert plan (Plan 1) did not allow much wave energy through and currents west of the causeway dissipated rapidly. The six- and nine-culvert plans (Plans 2 and 3, respectively) allowed more energy through the culverts which resulted in a slow westerly current migration. None of the plans, however, allowed for a continuous current flow downcoast of the causeway. The nine-culvert plan (Plan 3) resulted in current movement (from eddies) relatively close to the deep-draft port. Suspended sediments could possibly impact the port for this plan, so it was abandoned.

Results of sediment tracer experiments for the six-culvert plan (Plan 2) indicated that sediment in the area east of the causeway will move westerly along the shoreline to the causeway and pass through the shorewardmost culvert. Since the currents dissipated quickly the sediment material deposited in an area west of the causeway. There was not enough wave energy in this area to continue moving the bed-load material.

Examination of wave-induced current patterns and magnitudes for the 122- and 183-m (400- and 600-ft) openings in the causeway (Plans 4 and 5, respectively) revealed that current patterns east of the causeway were similar to existing conditions. Currents, however, moved westerly through the openings and continued moving downcoast (to the limits of the model). Both plans resulted in currents along the shoreline west of the causeway with similar velocities as those obtained east of the structure which should allow for a continuous current flow downcoast in a westerly direction. In general, the 183-m (600-ft) opening of Plan 5 resulted in slightly higher magnitudes at greater distances west of the causeway than the 122-m (400-ft) opening of Plan 4. The openings in the causeway for Plans 4 and 5 initiated at the most shoreward culvert studied for the previous plans and extended seaward. The most shoreward culvert was located immediately seaward of the shoreline (0.0-m (0.0-ft) swl), and the causeway at

this location had a vertical face representing a bridge abutment or bulkhead. The projection of the inner portion of the causeway into the surf zone created an eddy west (downcoast) of its location.

Results of sediment tracer experiments for the 183-m (600-ft) opening in the causeway (Plan 5) indicated that sediment in the area east of the causeway will move westerly along the shoreline, around the inner portion of the causeway, through the opening, and then continue to move westerly downcoast of the causeway. The projection of the inner portion of the causeway into the surf zone resulted in a clockwise eddy immediately downcoast. After the area in the lee of the inner portion of the causeway eventually filled in with sediment, the tracer began moving westerly downcoast. The westerly movement of sediment occurred in the immediate vicinity of the causeway. It should be noted that not enough shoreline west of the causeway was reproduced in the model (due to time and cost constraints) to determine the effects of the causeway and island on deposition of the shoreline in the intermediate and far field areas.

The inner portion of the causeway protruding into the surf zone caused eddies impacting current and sediment tracer patterns immediately west of the structure. Therefore, this portion of the causeway was removed indicating that pilings to support the causeway should be installed up the slope of the shoreline with an abutment, or bulkhead, constructed at the top of the slope out of the surf zone. The plan also entailed removal of an existing fillet (adjacent to the inner portion of the causeway) which represented a more natural slope in the area. Evaluation of experimental results indicated that the removal of the inner portion of the causeway and restoration of the shoreline in this area to a more natural state (Plan 6) resulted in improved wave-induced current patterns and sediment tracer patterns. Results revealed the plan eliminated the eddy along the shoreline west of the causeway that caused undesirable current and sediment patterns. In addition, results indicated that Plan 6 had no adverse impacts on current patterns and magnitudes elsewhere in the model.

5 Conclusions

Based on the results, the conclusions of the coastal model investigation reported herein, were as follows:

a. For existing conditions, wave height experiments indicated that wave heights of 0.46 m (1.5 ft) in the small-boat harbor and 0.27 m (0.9 ft) in the deep-draft port will occur for storm waves generated in deep water.

b. For existing conditions, wave height experiments and visual observations indicated that wave conditions east of the causeway were greater for locally-generated wind waves (due to wave growth over the shallow reef) than for the larger waves generated in deep water since they broke and expended their energy on the edge of the reef.

c. Wave-induced current patterns for existing conditions generally indicated westerly movement along the shoreline (east of the harbor and causeway complex) and then movement seaward along the causeway. Experiments indicated that current velocities of over 1.22 m/s (4.0 fps) along the causeway and 2.13 m/s (7.0 fps) through the gap in the small-boat harbor breakwater will occur for incident waves generated over the shallow reef.

d. Sediment tracer experiments for existing conditions indicated that sediment east of the causeway will move westerly along the shoreline and then seaward adjacent to the causeway resulting in deposits in these areas.

e. None of the improvement plans studied revealed any adverse impacts on wave conditions in the existing small-boat harbor or the deep-draft port.

f. Wave-induced current patterns for the improvement plans with culverts installed through the causeway (Plans 1-3) indicated that currents will jet through the culverts with relatively high velocities, meander in eddies, and dissipate or only slowly migrate westerly. The plans allowed for no continuous current flow downcoast of the causeway.

g. Sediment tracer experiments for the six-culvert plan (Plan 2) indicated that sediment east of the causeway will move westerly along the shoreline to the causeway, pass through the shorewardmost culvert, and deposit in an area west of the causeway.

h. Wave-induced current patterns and magnitudes for the openings in the causeway (Plans 4 and 5) indicated a continuous current flow downcoast in a westerly direction. Velocities along the shoreline west of the causeway were similar to those obtained east of the structure. However, the 183-m (600-ft) opening of Plan 5 resulted in slightly greater velocities at greater distances west of the causeway than the 122-m (400-ft) opening of Plan 4.

i. Sediment tracer experiments for the 183-m (600-ft) opening in the causeway (Plan 5) indicated that sediment east of the causeway will move westerly along the shoreline, around the inner portion of the causeway, through the opening, and continue moving westerly downcoast of the causeway.

j. Removal of the inner portion of the causeway and restoration of the shoreline to a more natural state (i.e., removal of existing fillet) in this area (Plan 6) will result in improved wave-induced current patterns and sediment patterns (i.e., eddies along the shoreline will be eliminated).

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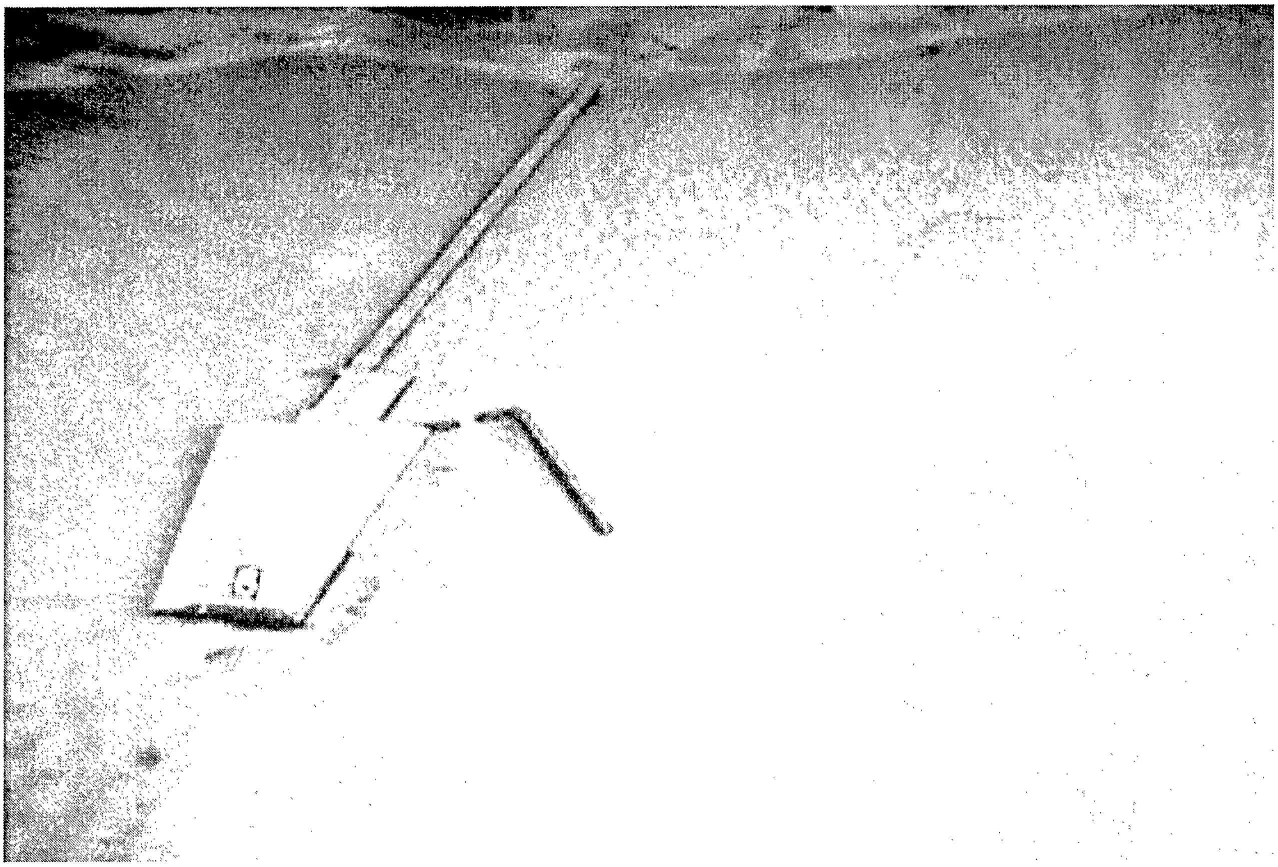


Photo 1. Typical wave patterns for existing conditions; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

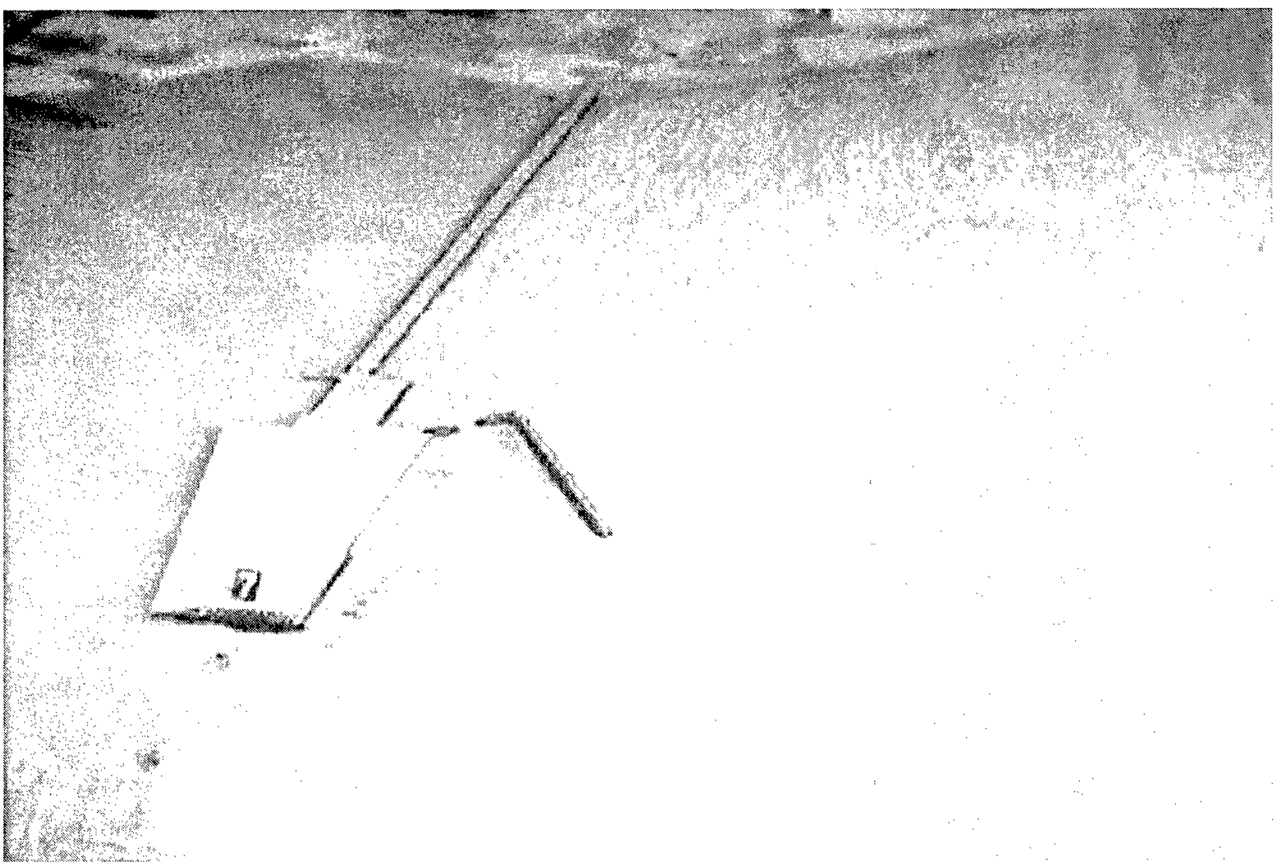


Photo 2. Typical wave patterns for existing conditions; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

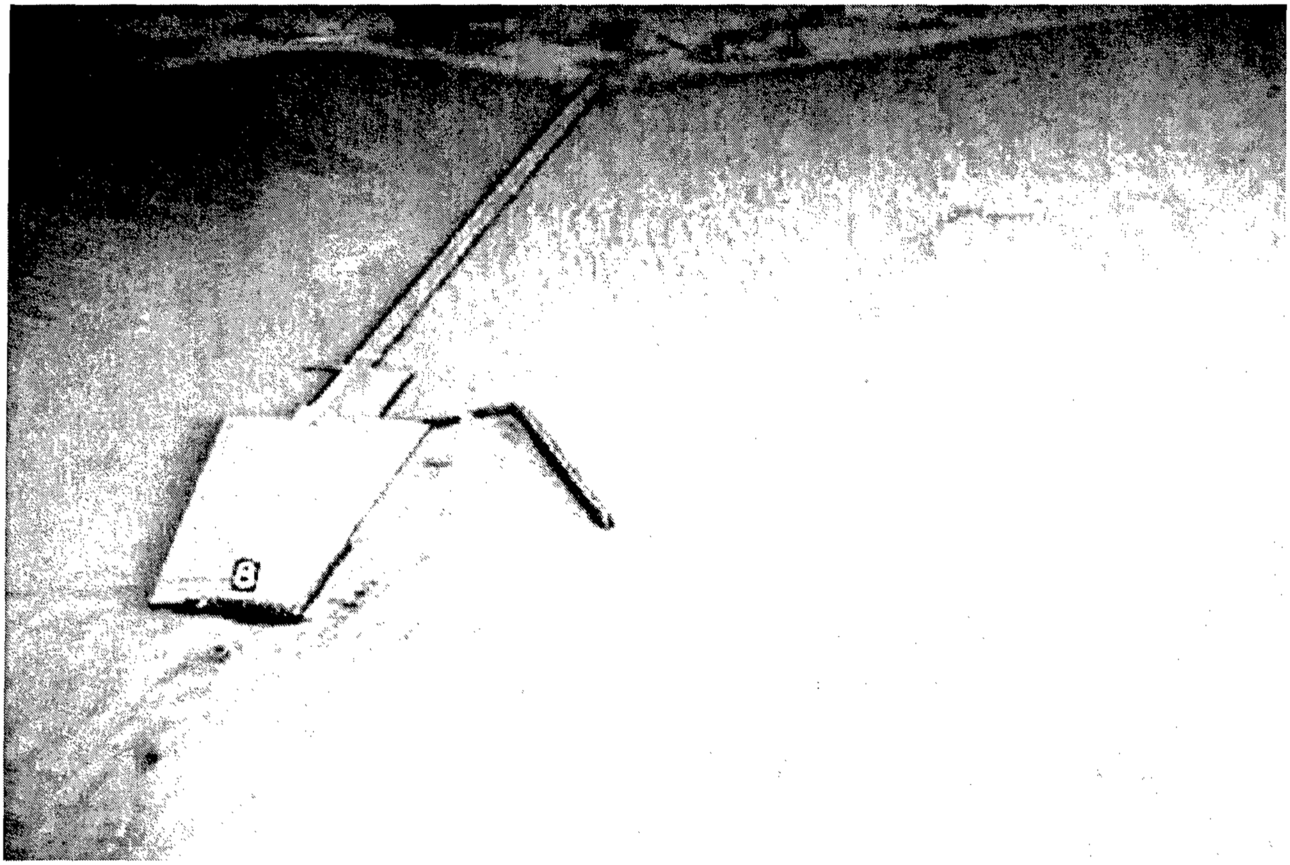


Photo 3. Typical wave patterns for existing conditions; 4.7-sec, 1.2-m (4-ft) waves from 90 deg

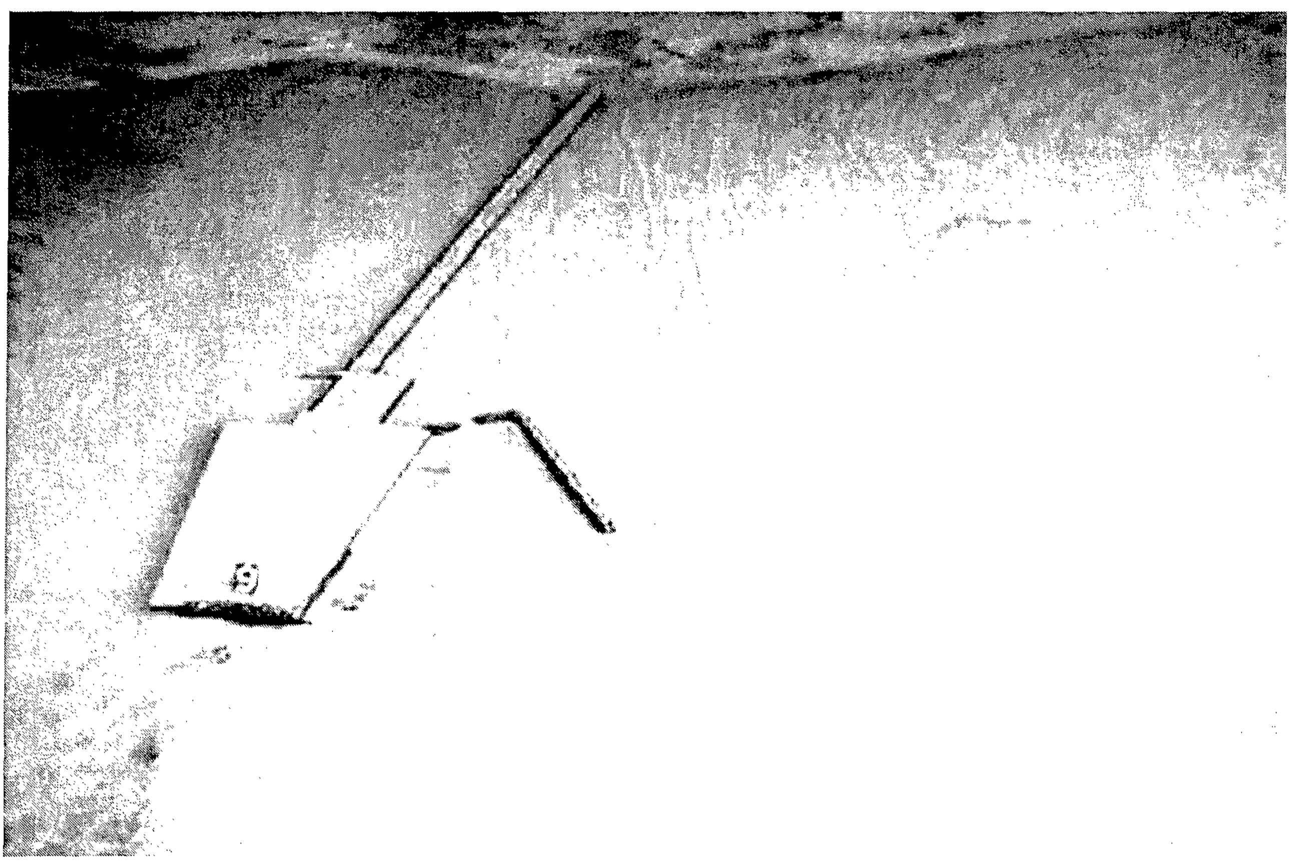


Photo 4. Typical wave patterns for existing conditions; 5.7-sec, 2.1-m (7-ft) waves from 90 deg

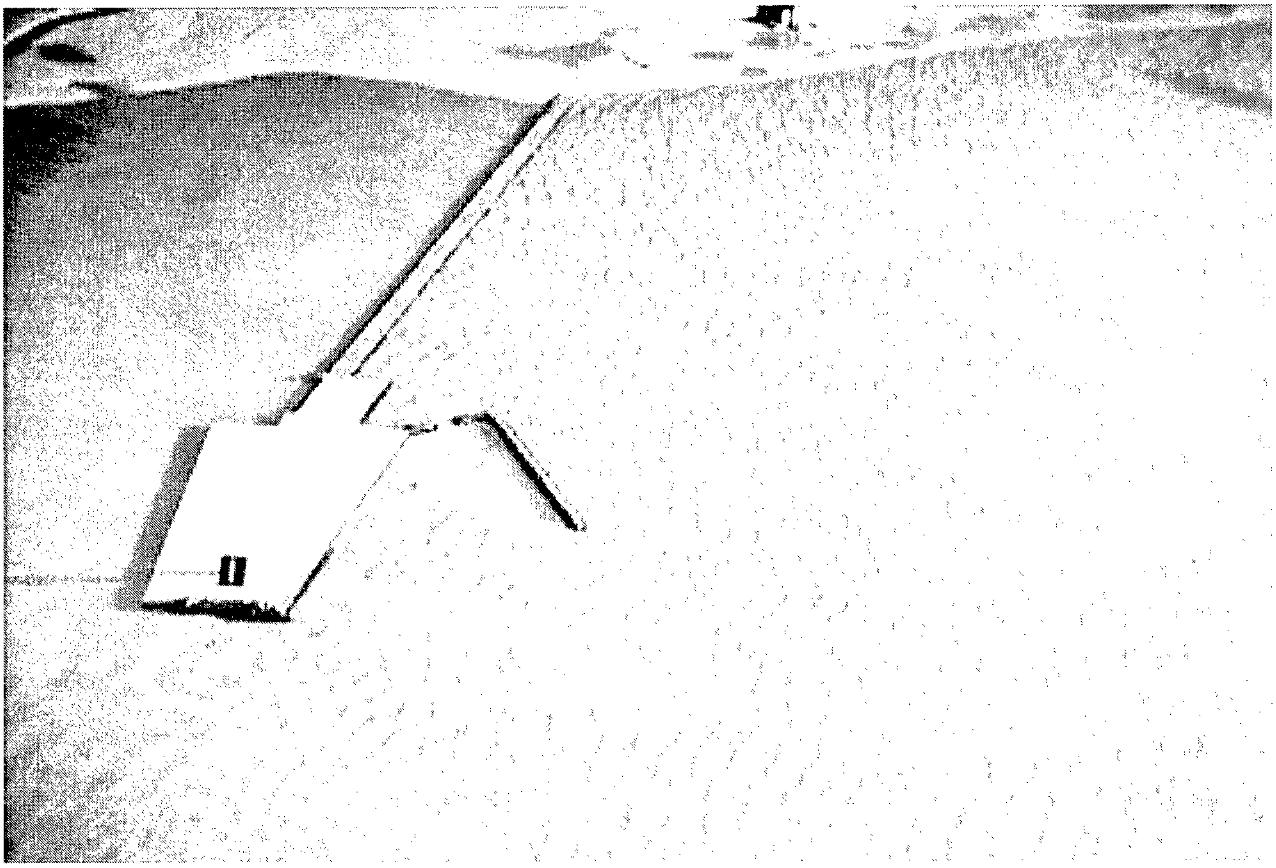


Photo 5. Typical wave patterns for existing conditions; 2.7-sec, 0.4-m (1.3-ft) waves from 110 deg

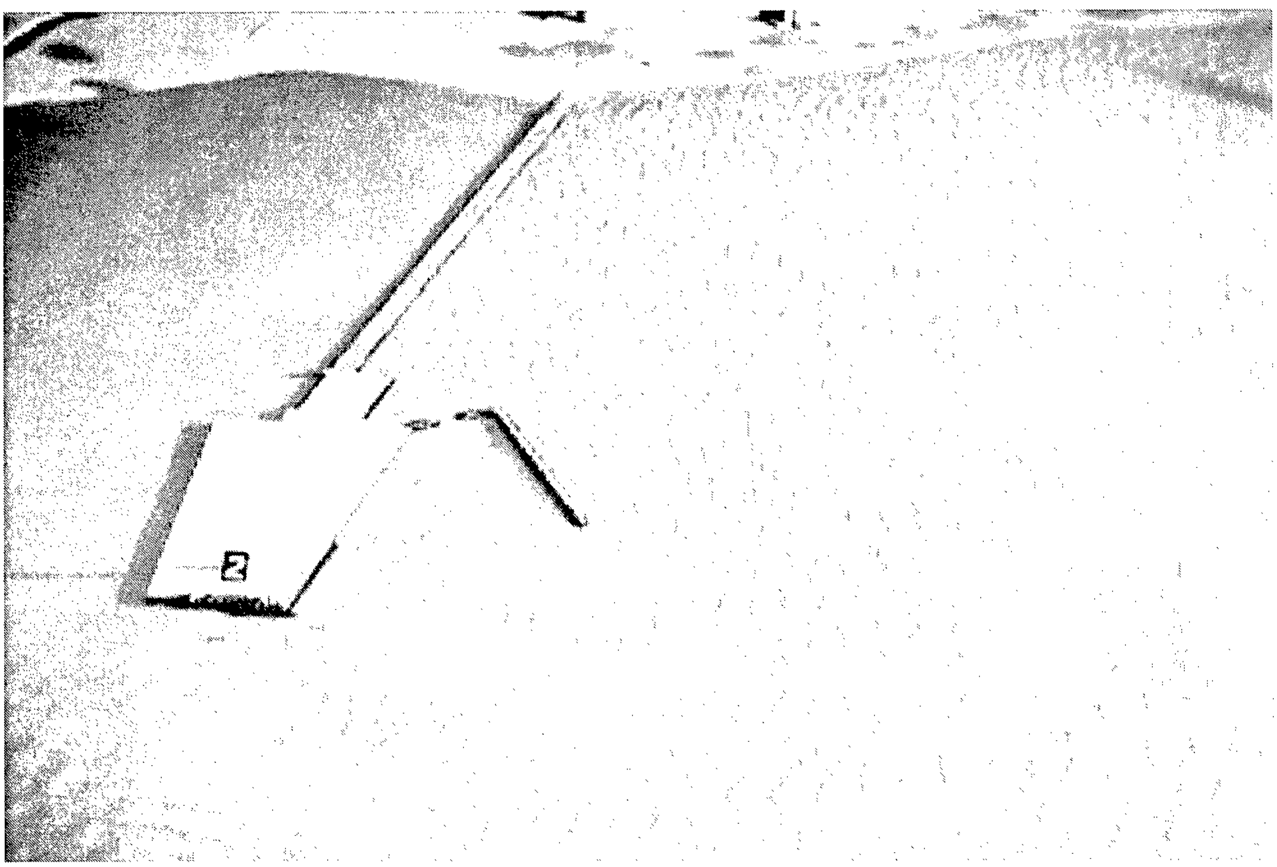


Photo 6. Typical wave patterns for existing conditions; 3.2-sec, 0.55-m (1.8-ft) waves from 110 deg

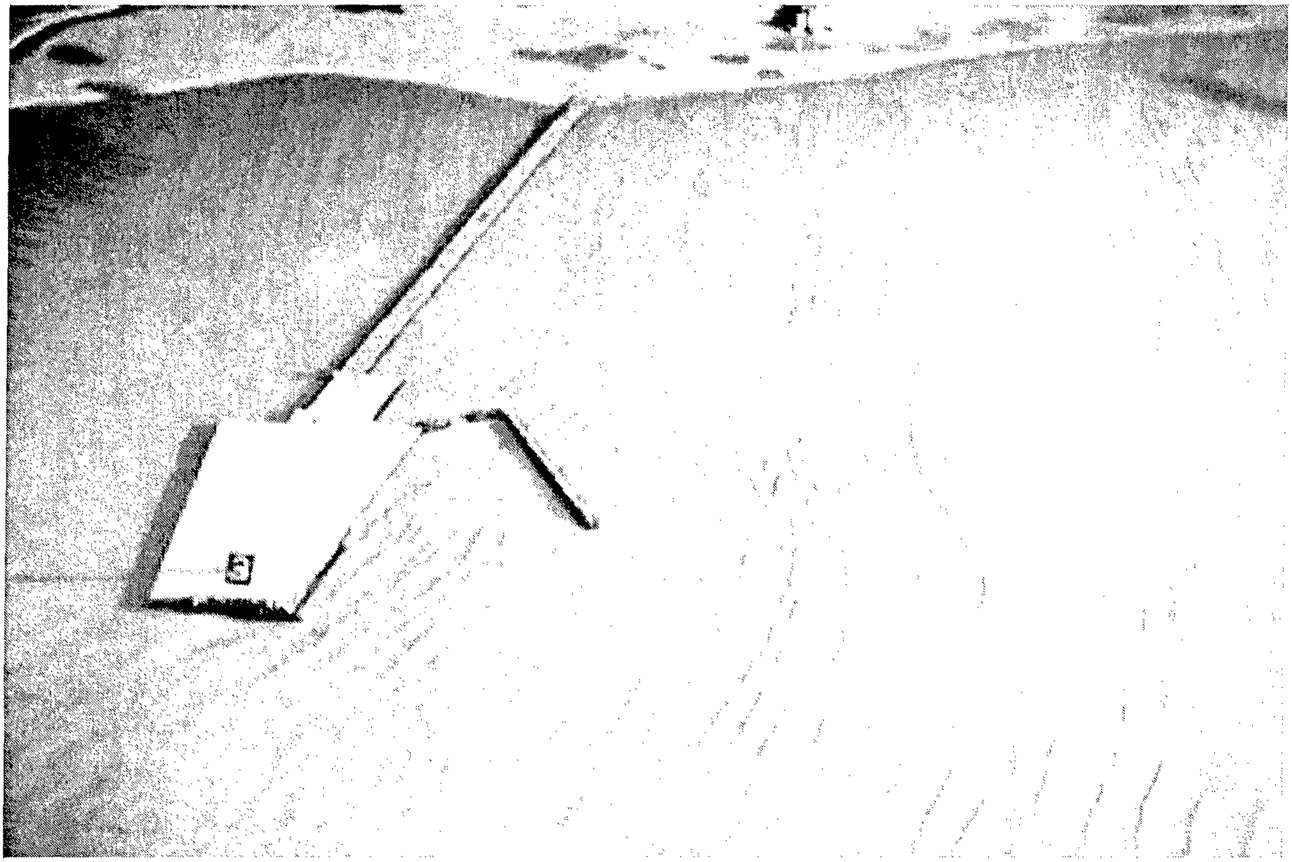


Photo 7. Typical wave patterns for existing conditions; 4.7-sec, 1.2-m (4-ft) waves from 110 deg

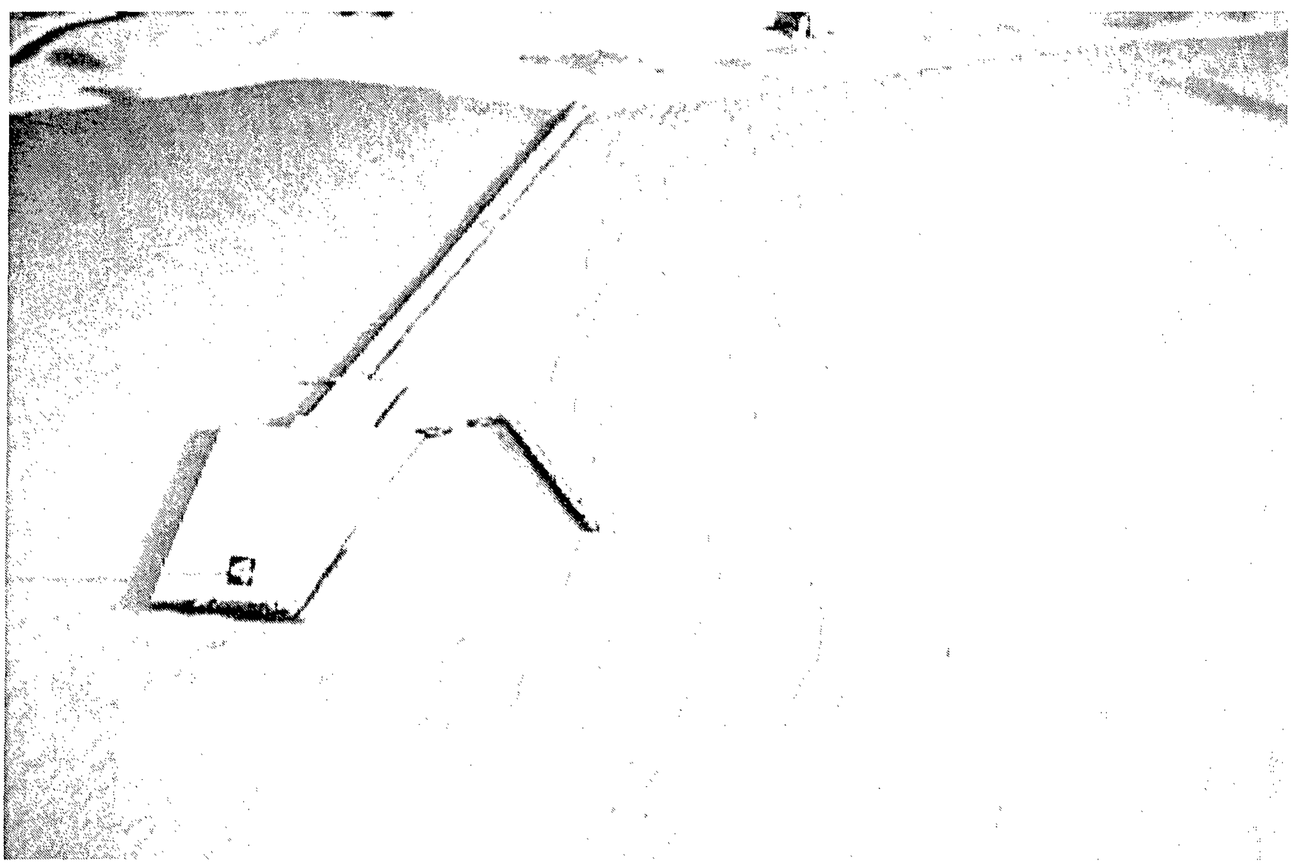


Photo 8. Typical wave patterns for existing conditions; 5.7-sec, 2.1-m (7-ft) waves from 110 deg

Photo 9. Typical wave and current patterns for existing conditions; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

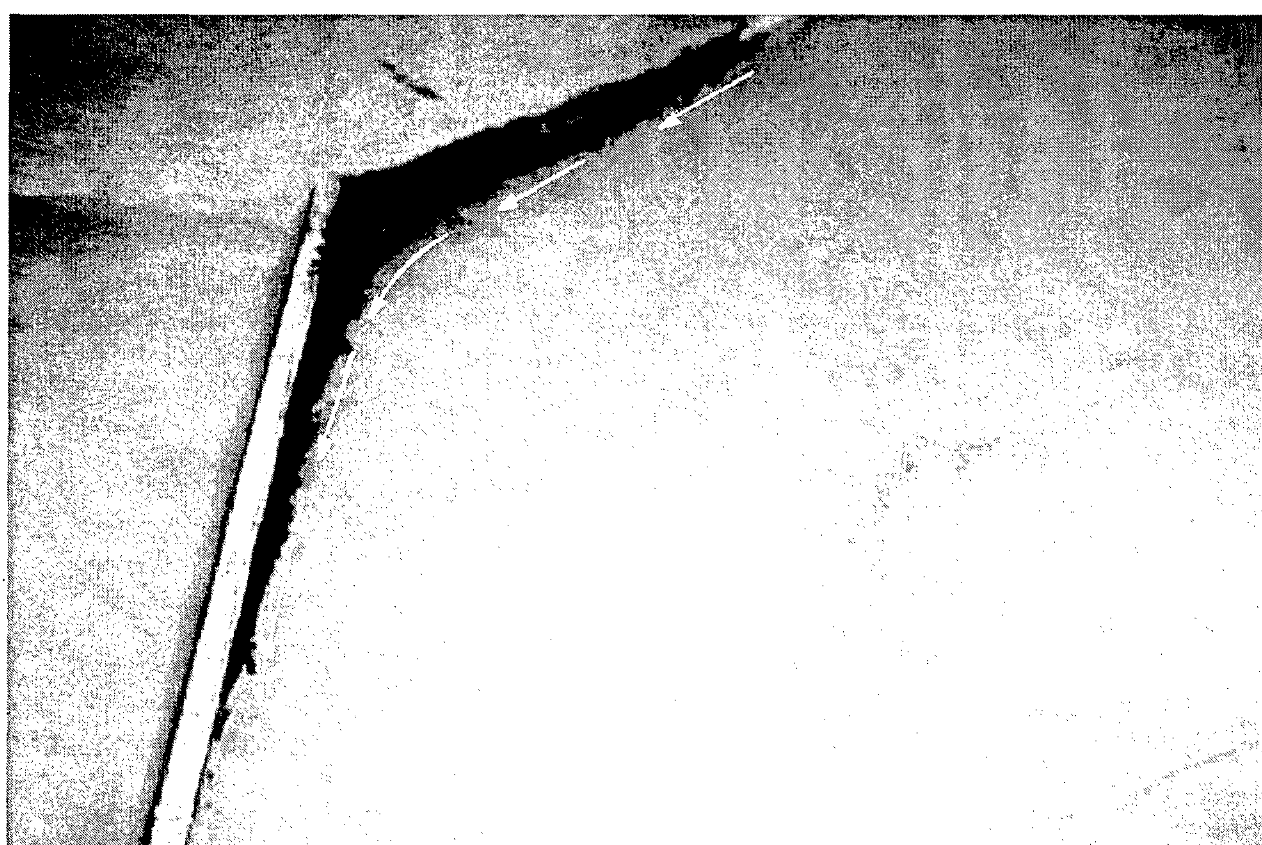


Photo 10. General movement of tracer material and subsequent deposits for existing conditions; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

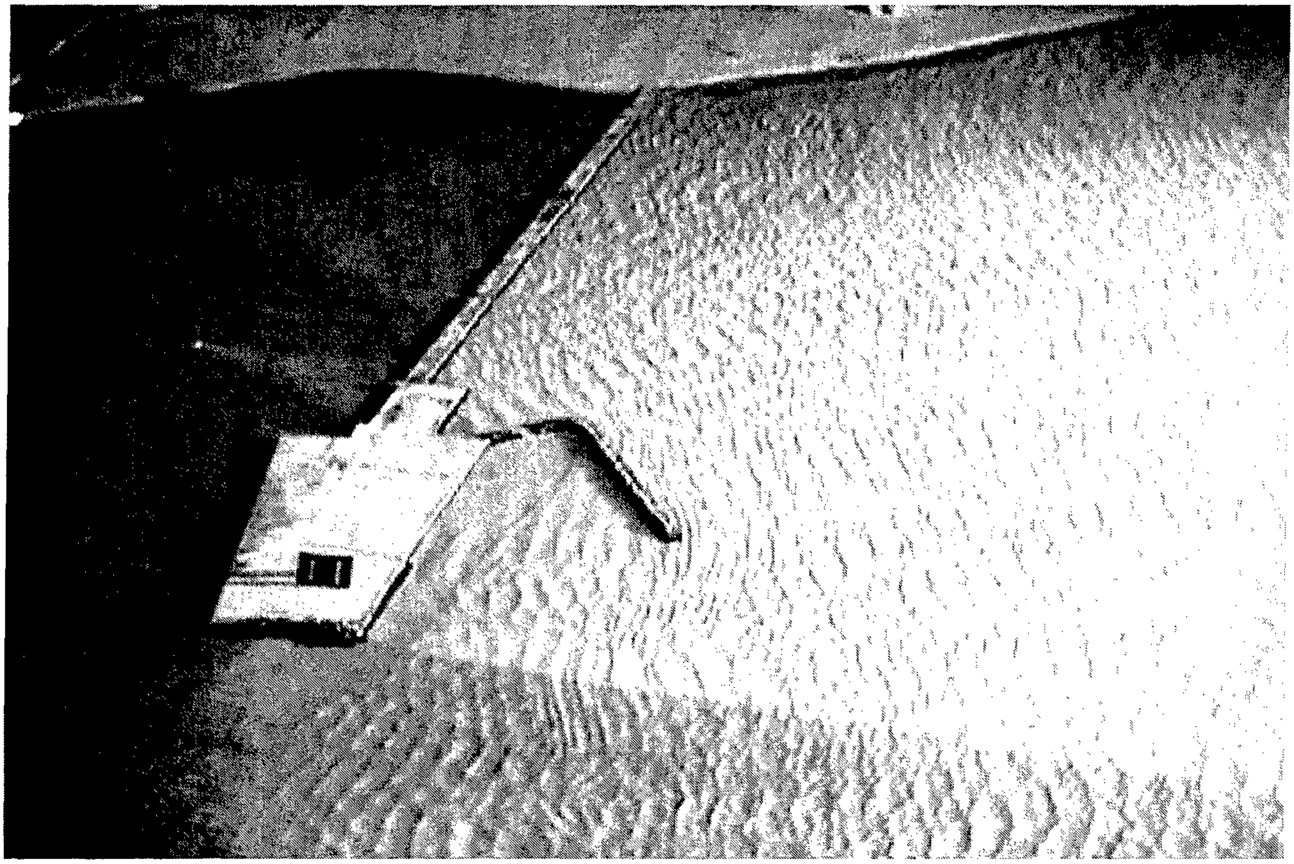


Photo 11. Typical wave patterns for Plan 1; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

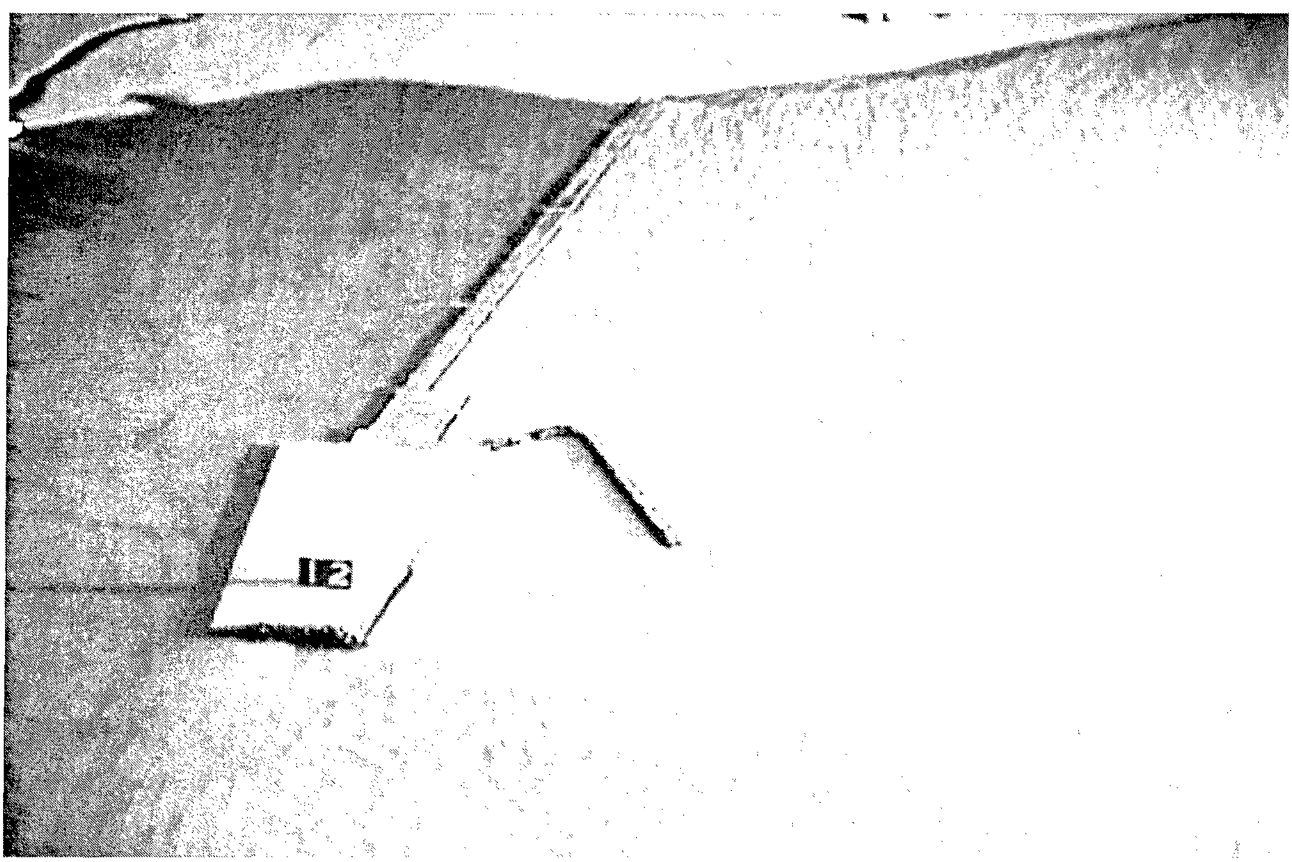


Photo 12. Typical wave patterns for Plan 1; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

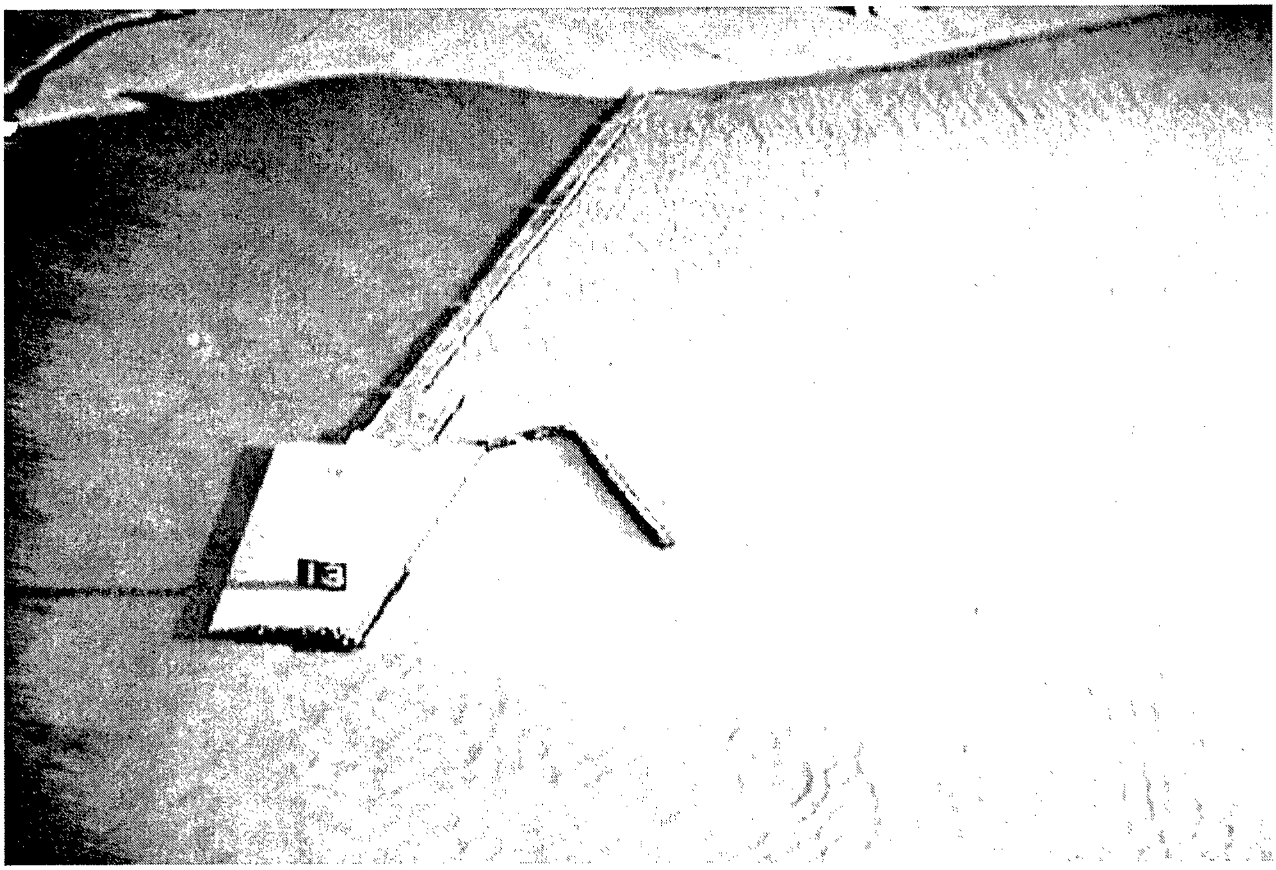


Photo 13. Typical wave patterns for Plan 1; 4.7-sec, 1.2-m (4-ft) waves from 90 deg

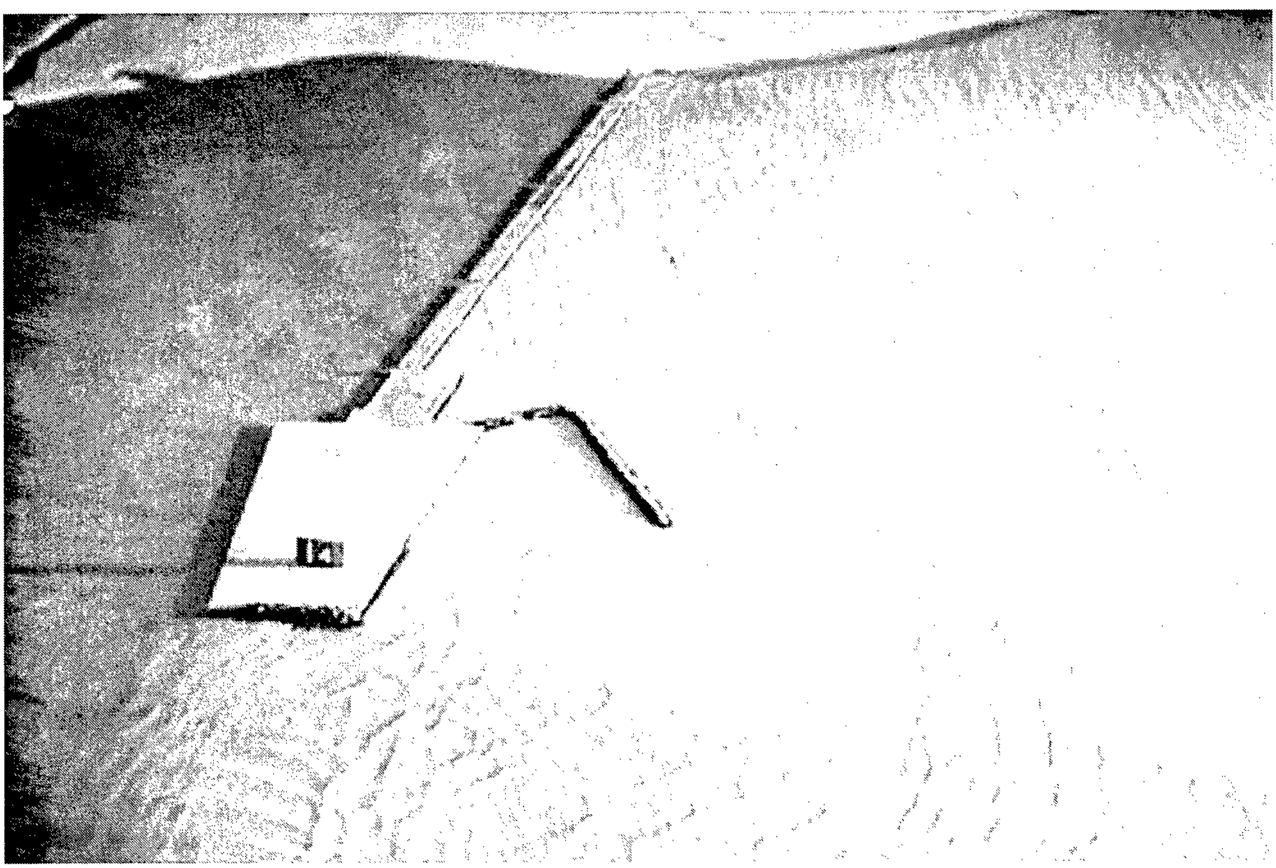


Photo 14. Typical wave patterns for Plan 1; 5.7-sec, 2.1-m (7-ft) waves from 90 deg

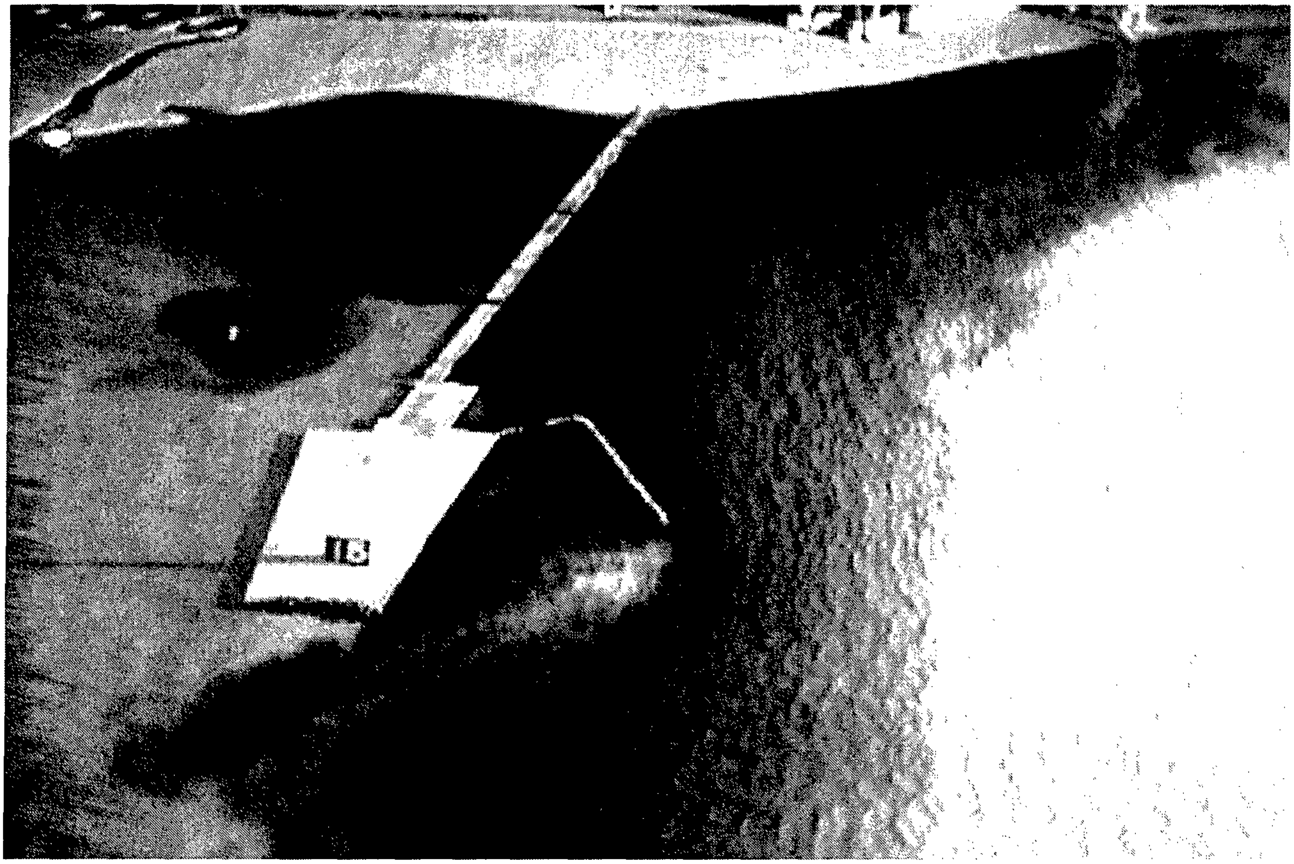


Photo 15. Typical current patterns for Plan 1; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

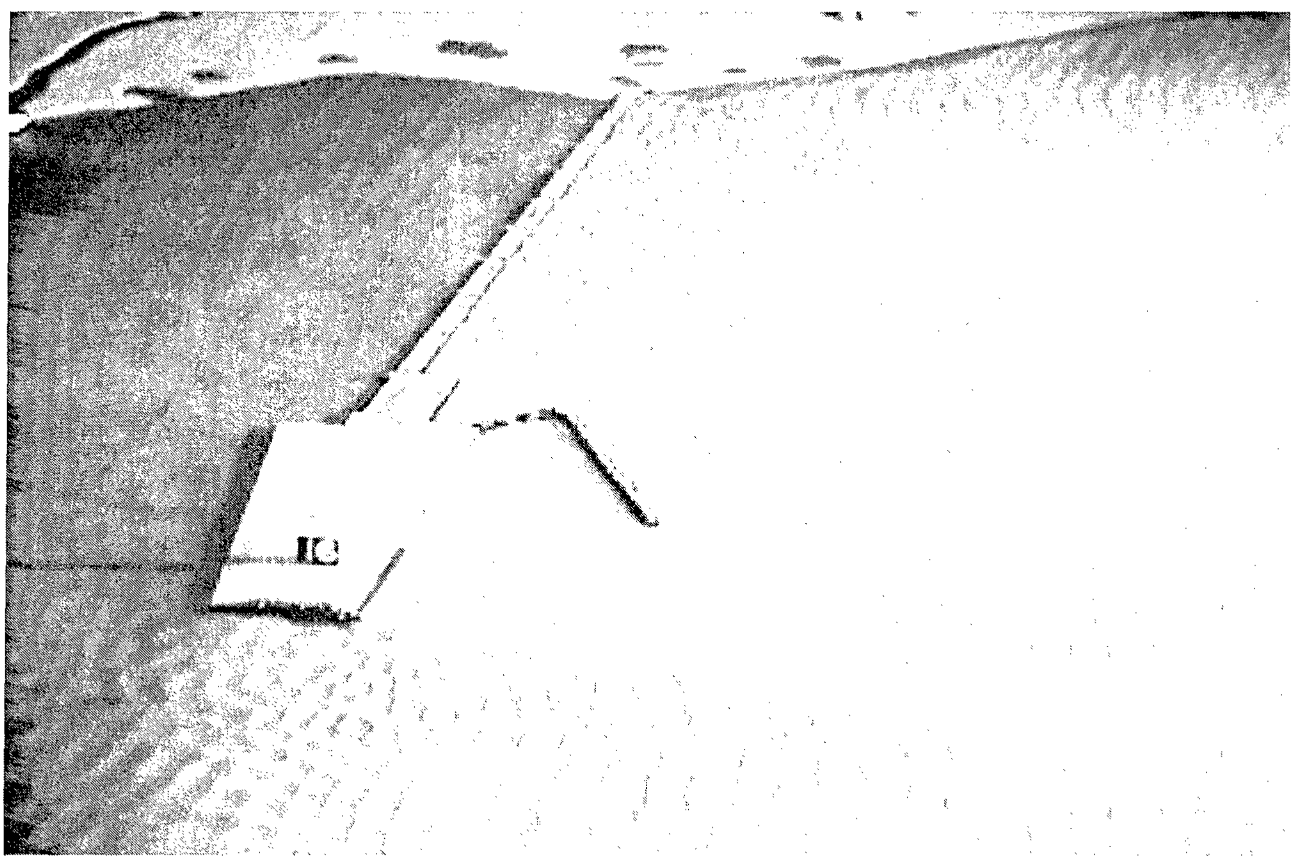


Photo 16. Typical wave patterns for Plan 2; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

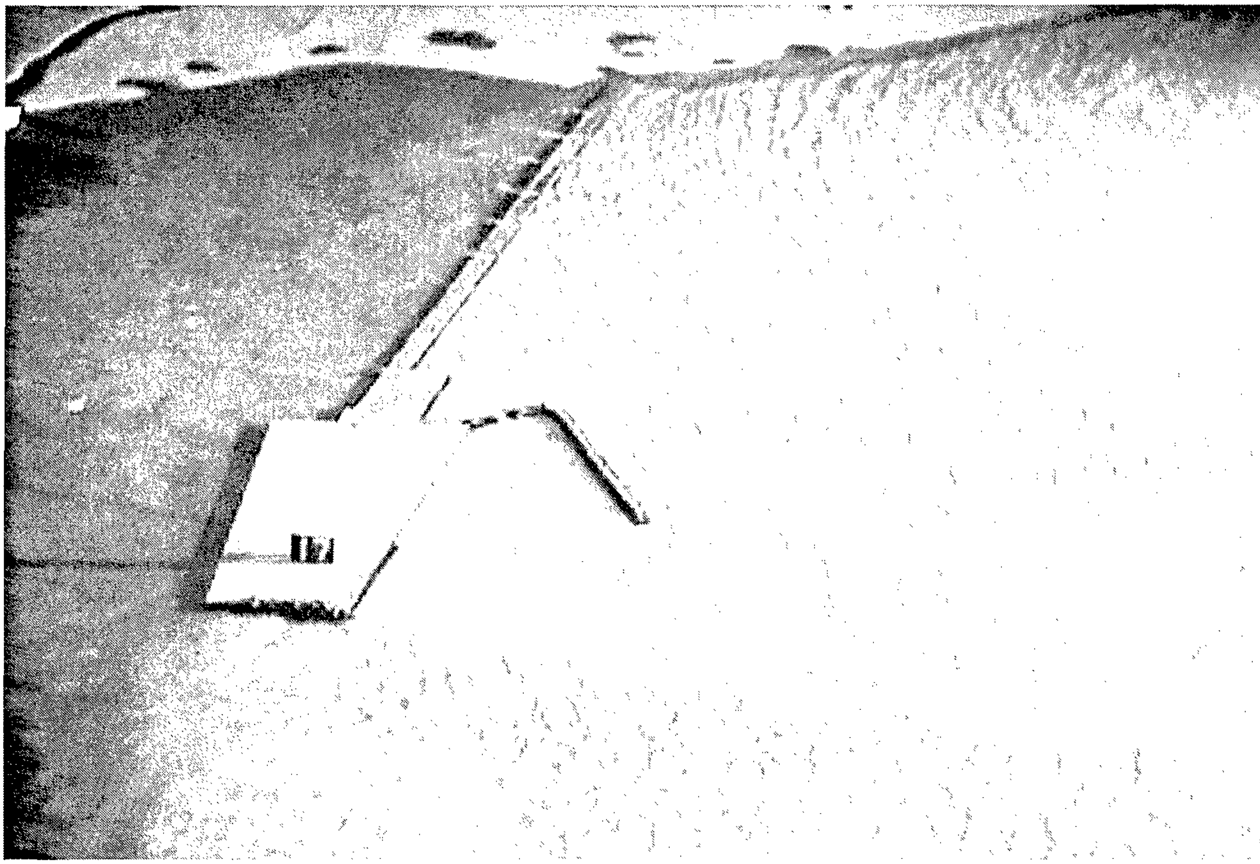


Photo 17. Typical wave patterns for Plan 2; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

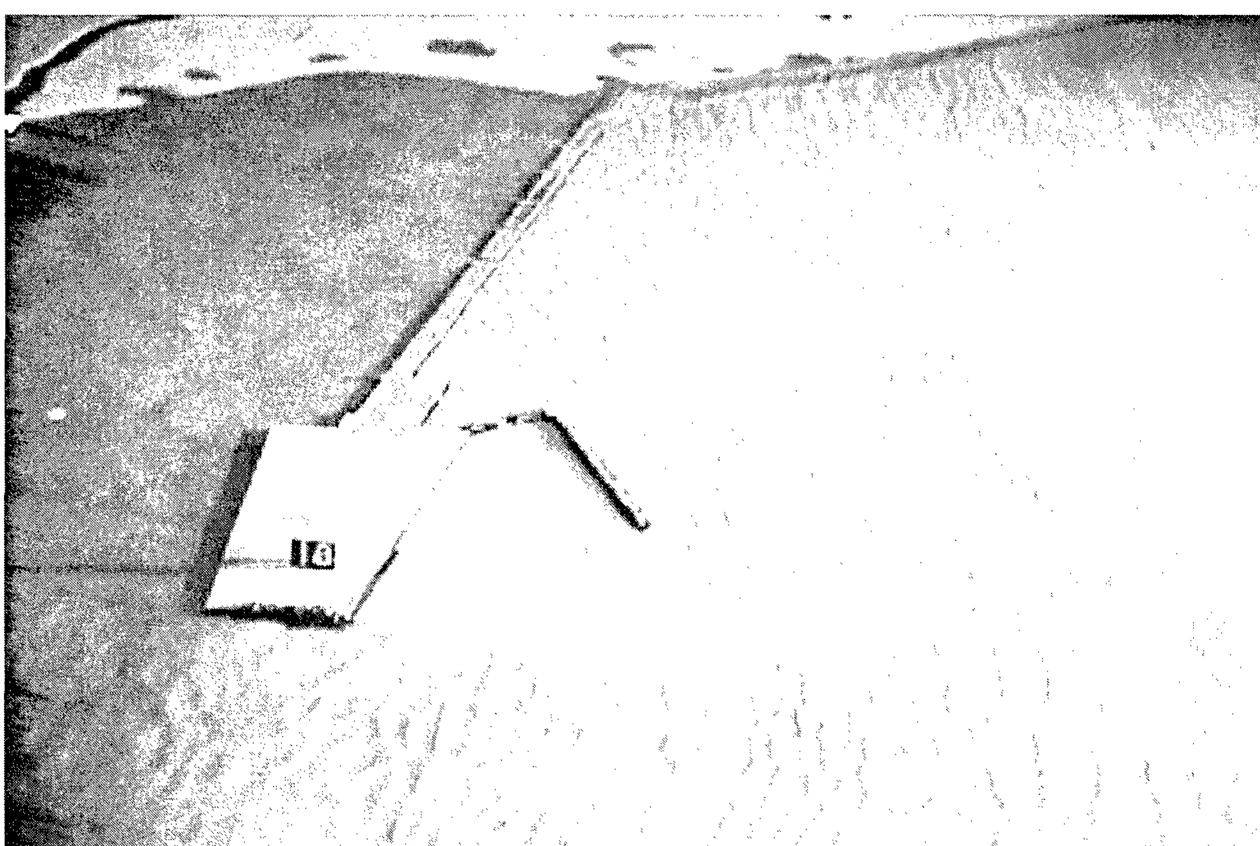


Photo 18. Typical wave patterns for Plan 2; 4.7-sec, 1.2-m (4-ft) waves from 90 deg

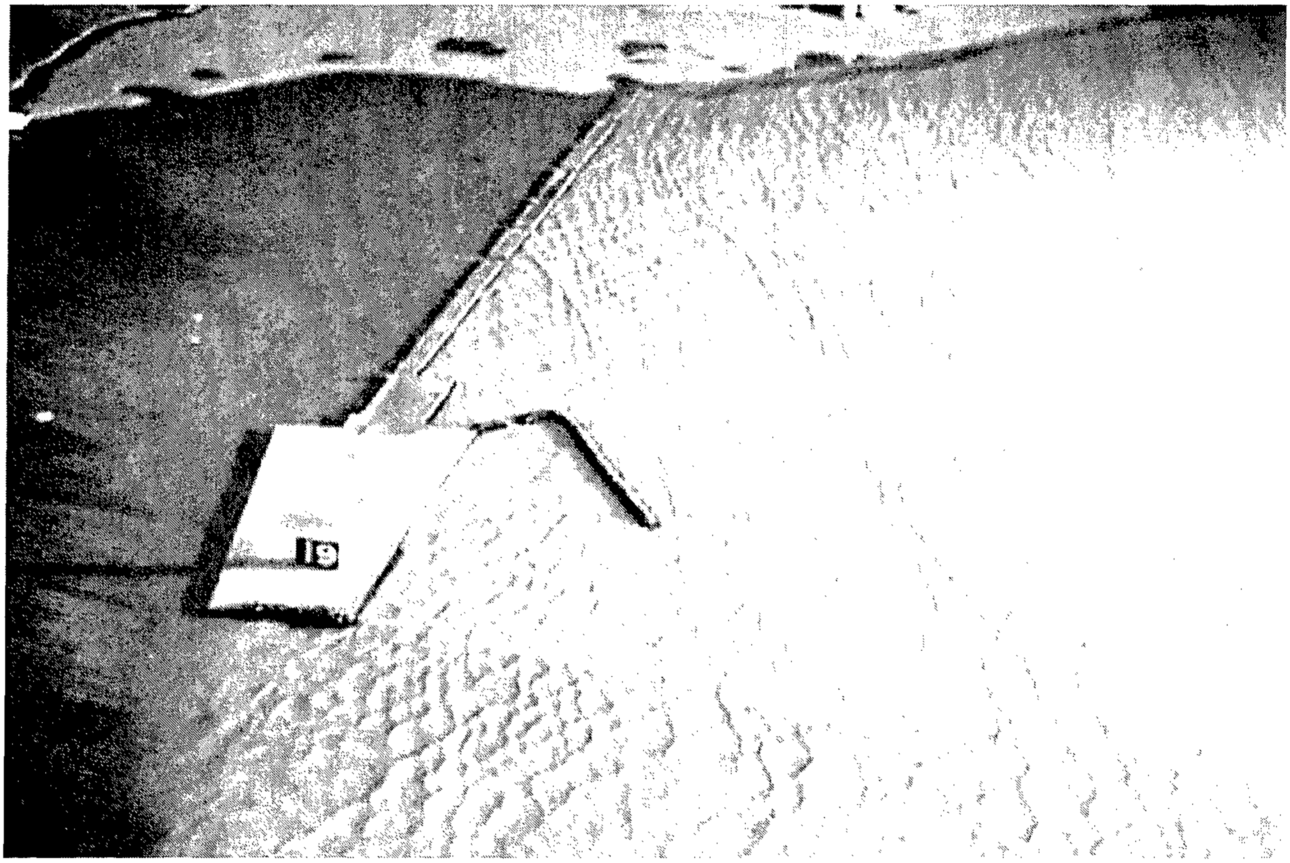


Photo 19. Typical wave patterns for Plan 2; 5.7-sec, 2.1-m (7-ft) waves from 90 deg

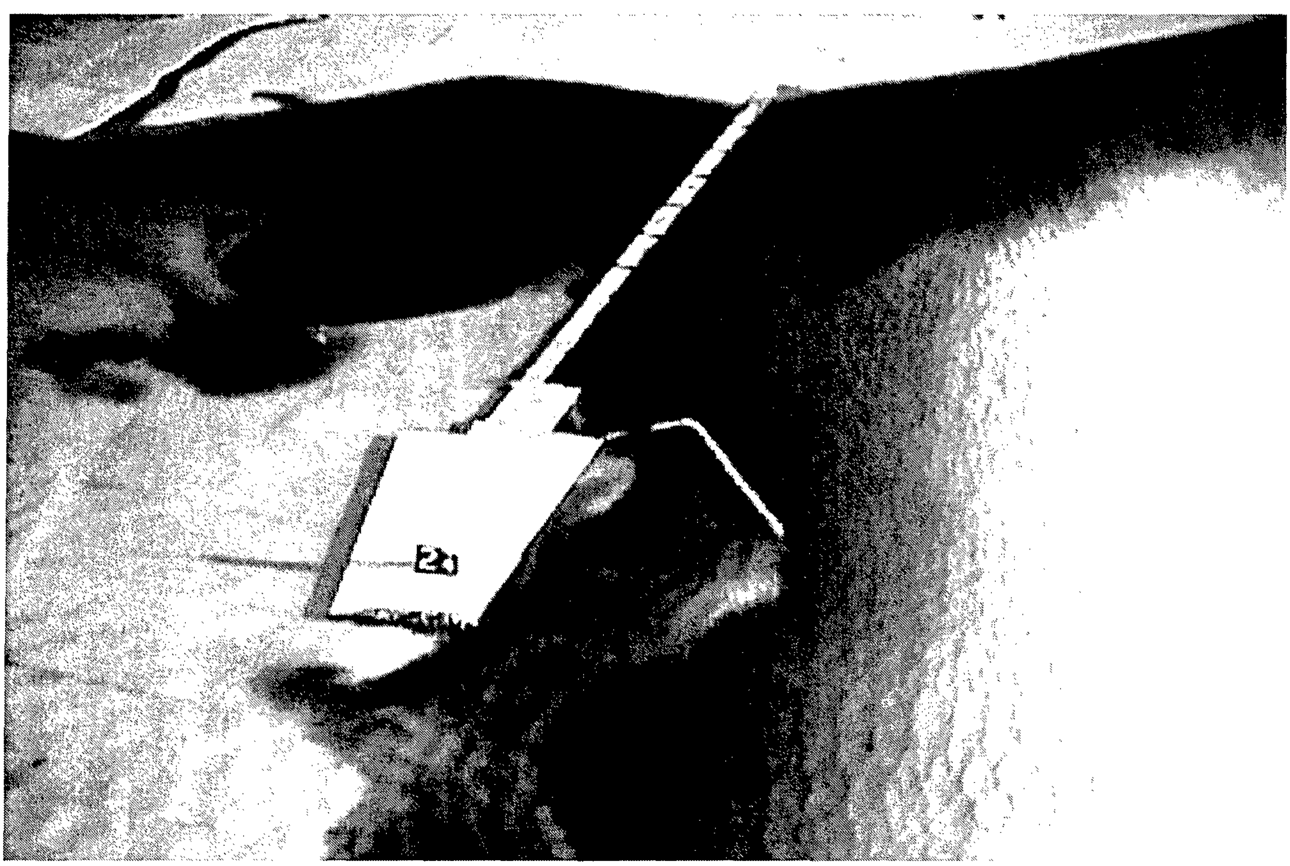


Photo 20. Typical current patterns for Plan 2; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

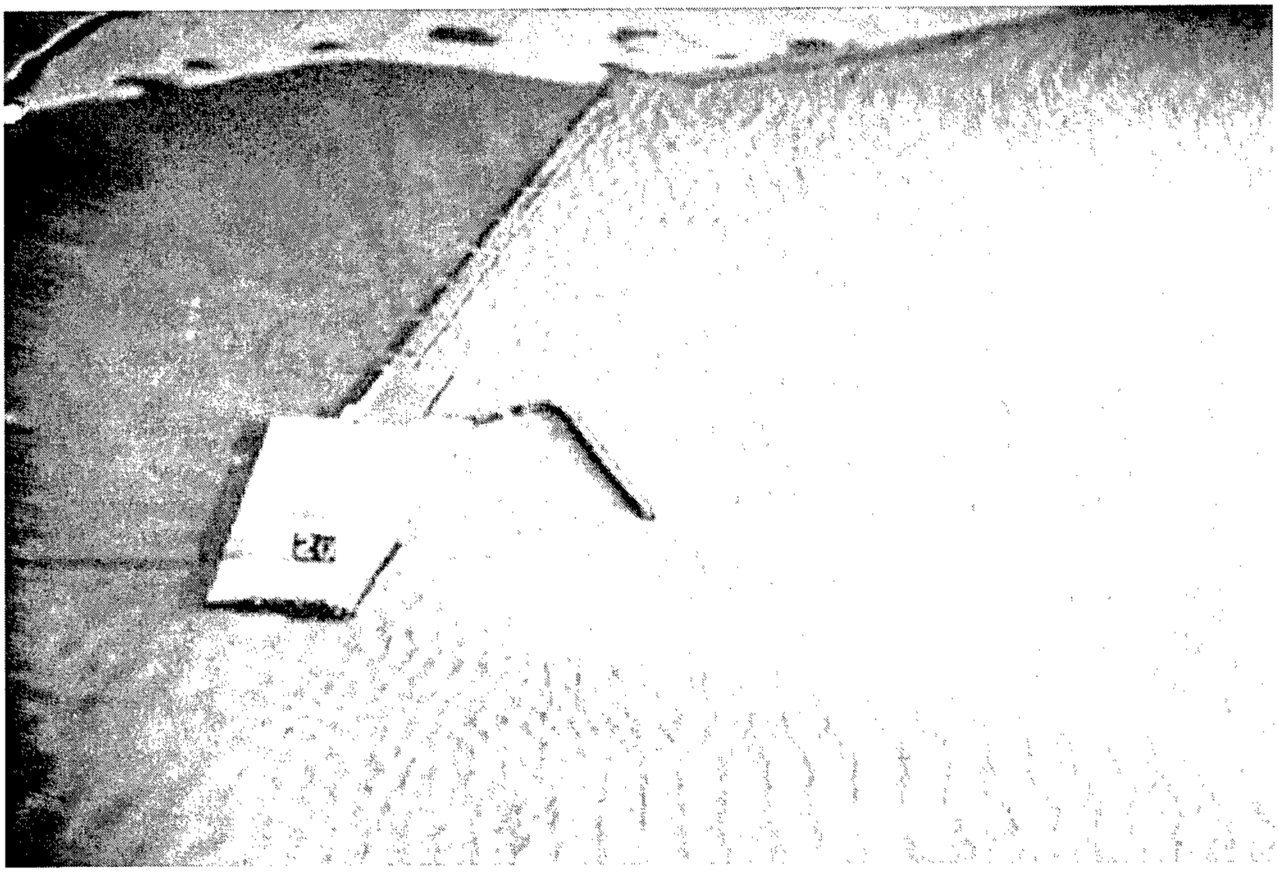


Photo 21. Typical wave patterns for Plan 3; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

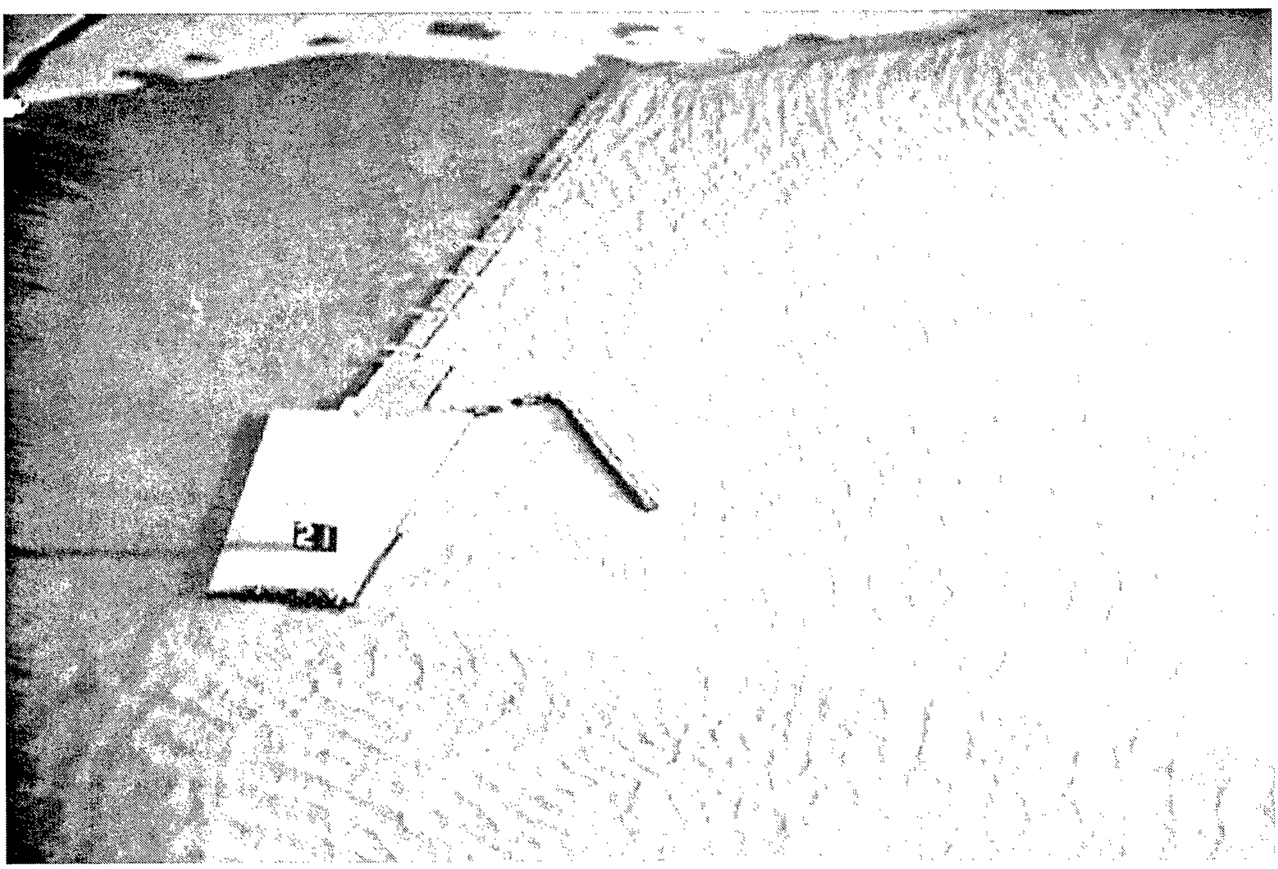


Photo 22. Typical wave patterns for Plan 3; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

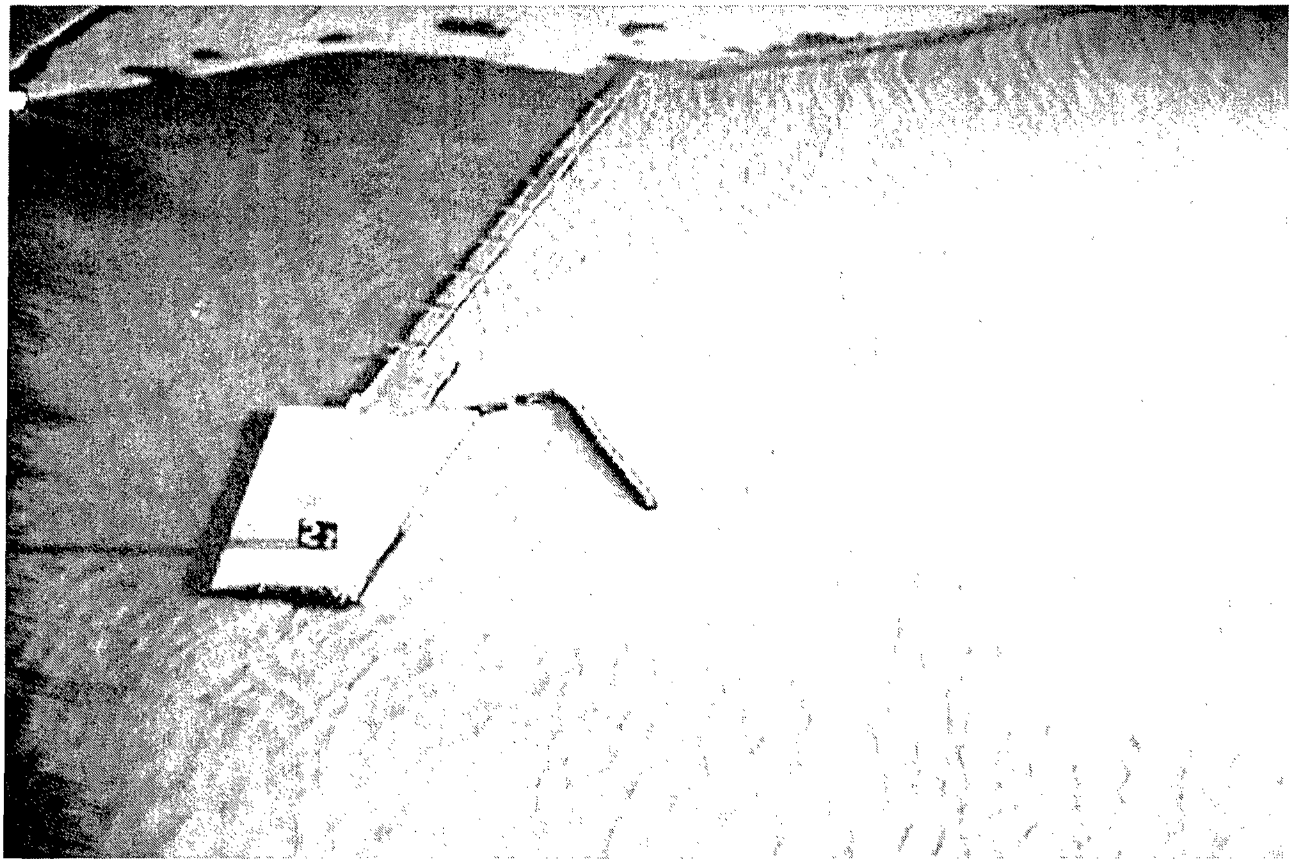


Photo 23. Typical wave patterns for Plan 3; 4.7-sec, 1.2-m (4-ft) waves from 90 deg

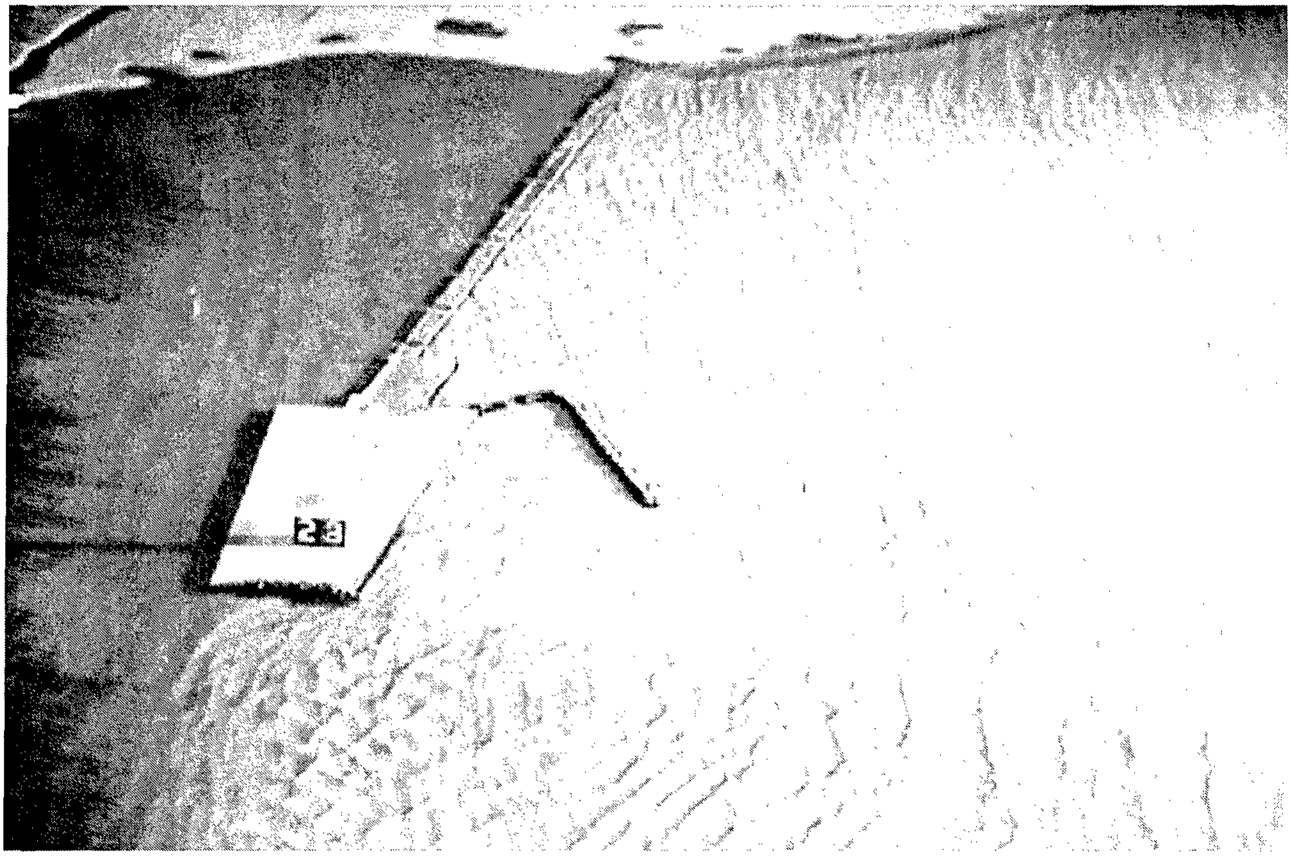


Photo 24. Typical wave patterns for Plan 3; 5.7-sec, 2.1-m (7-ft) waves from 90 deg

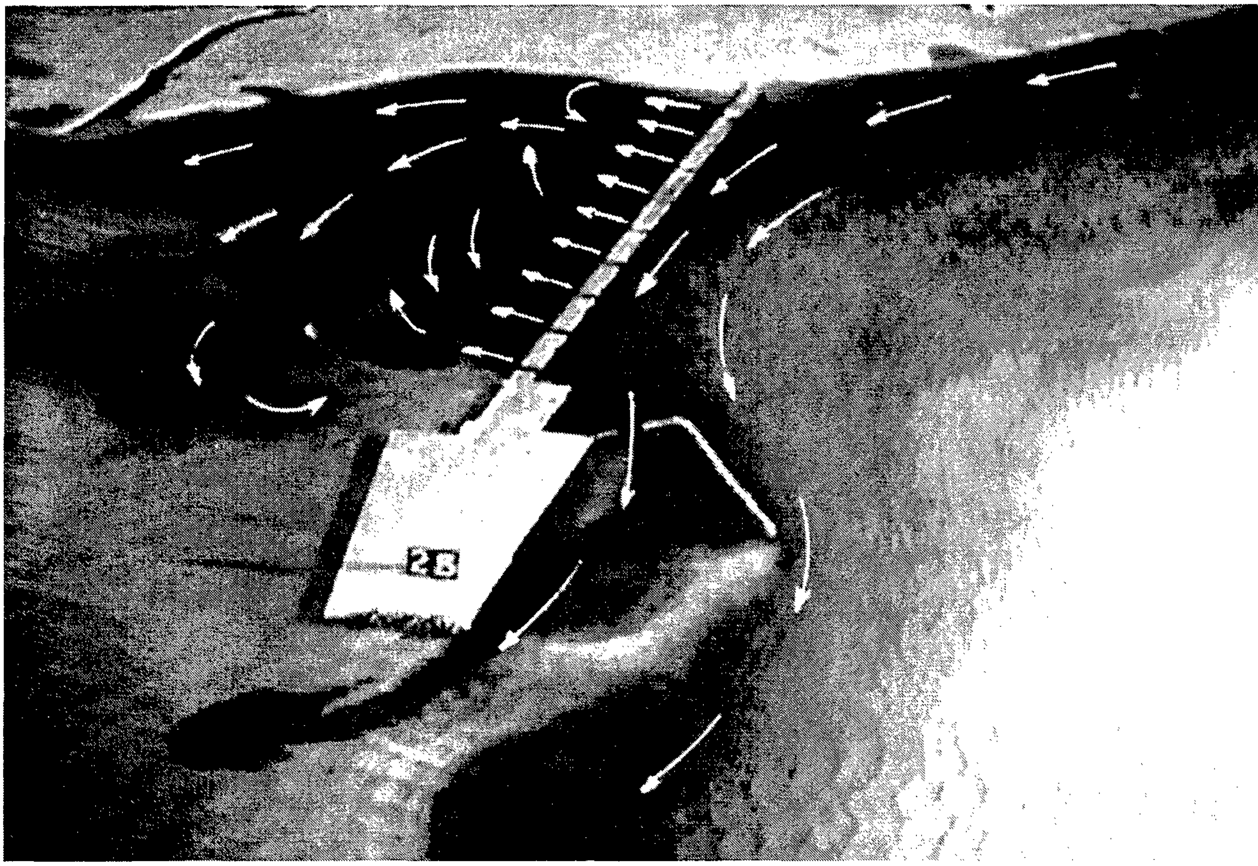


Photo 25. Typical wave and current patterns for Plan 3; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

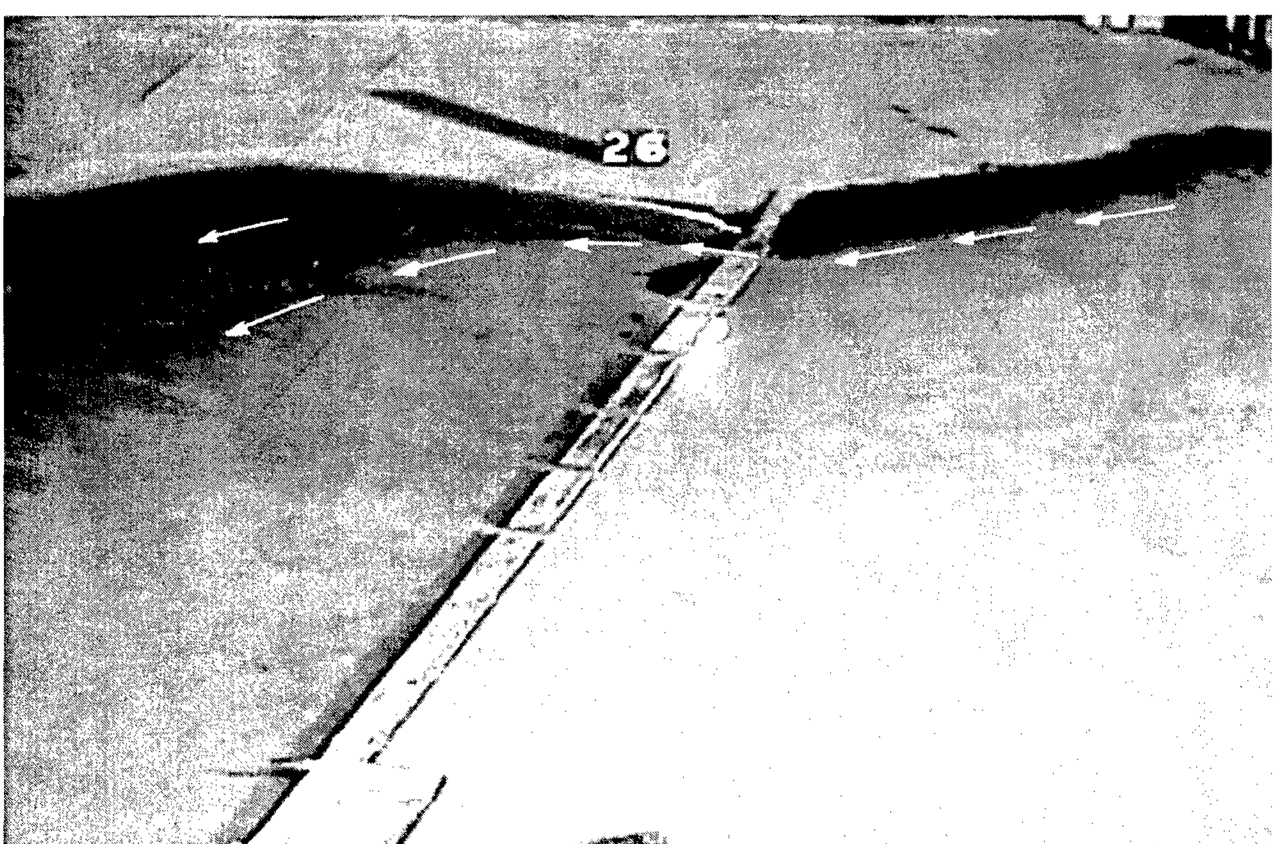


Photo 26. General movement of tracer material and subsequent, deposits for Plan 2; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

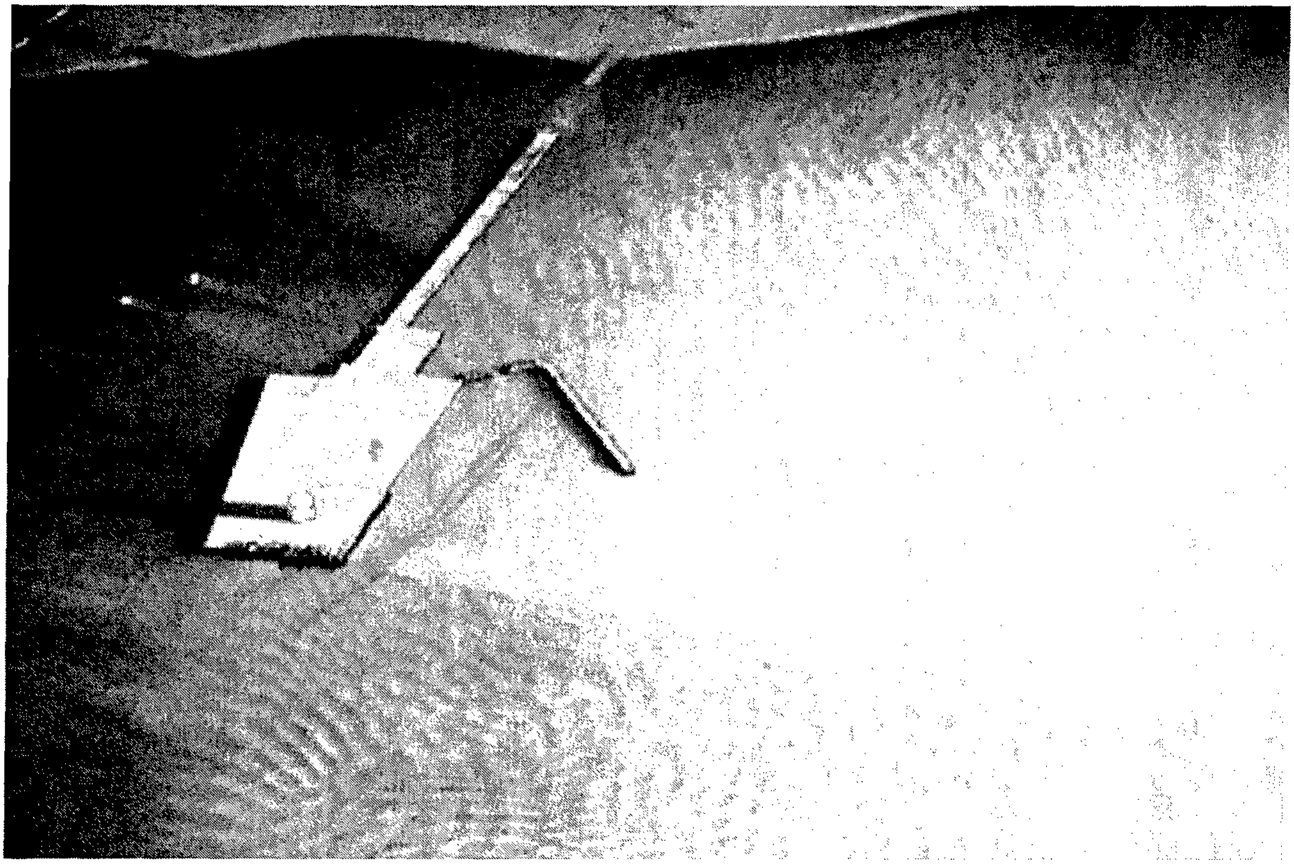


Photo 27. Typical wave patterns for Plan 4; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

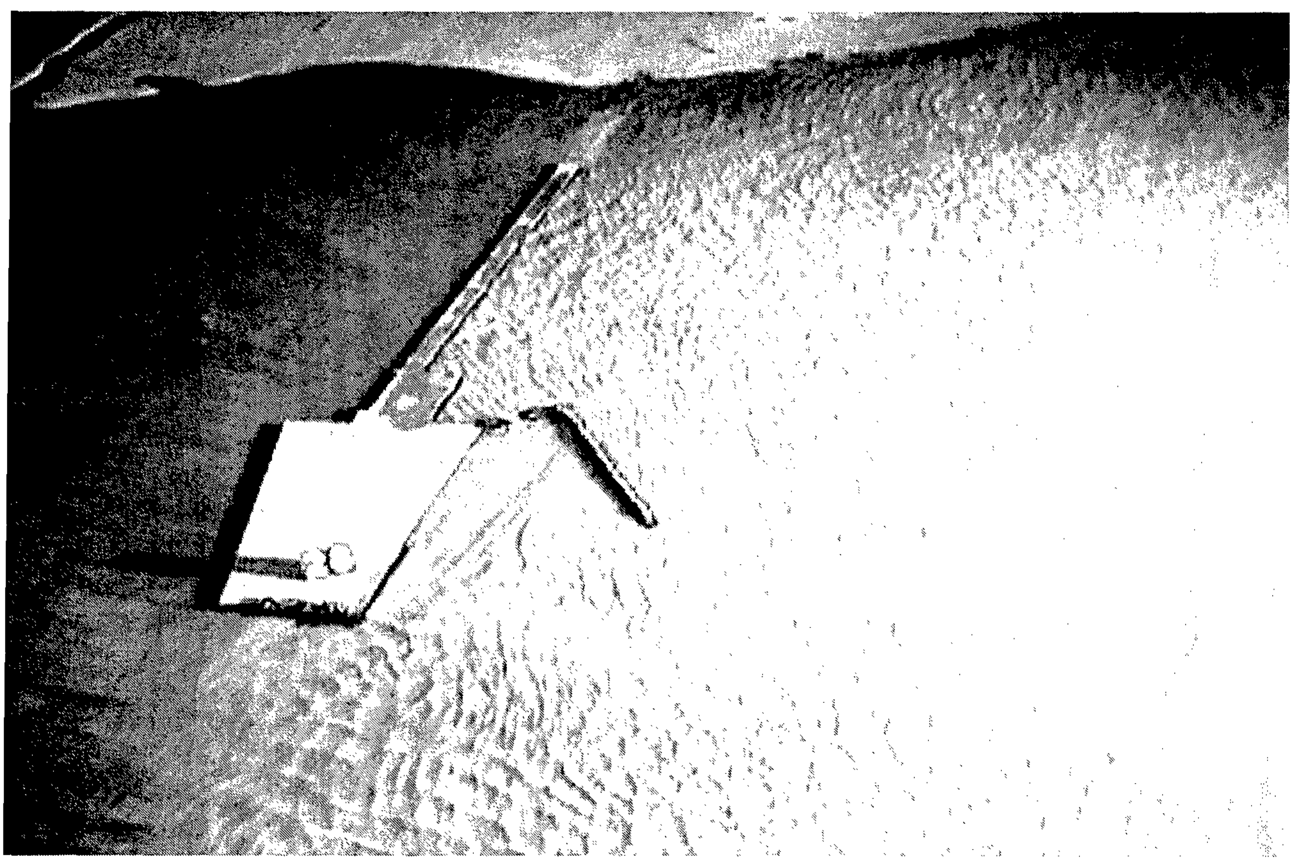


Photo 28. Typical wave patterns for Plan 4; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

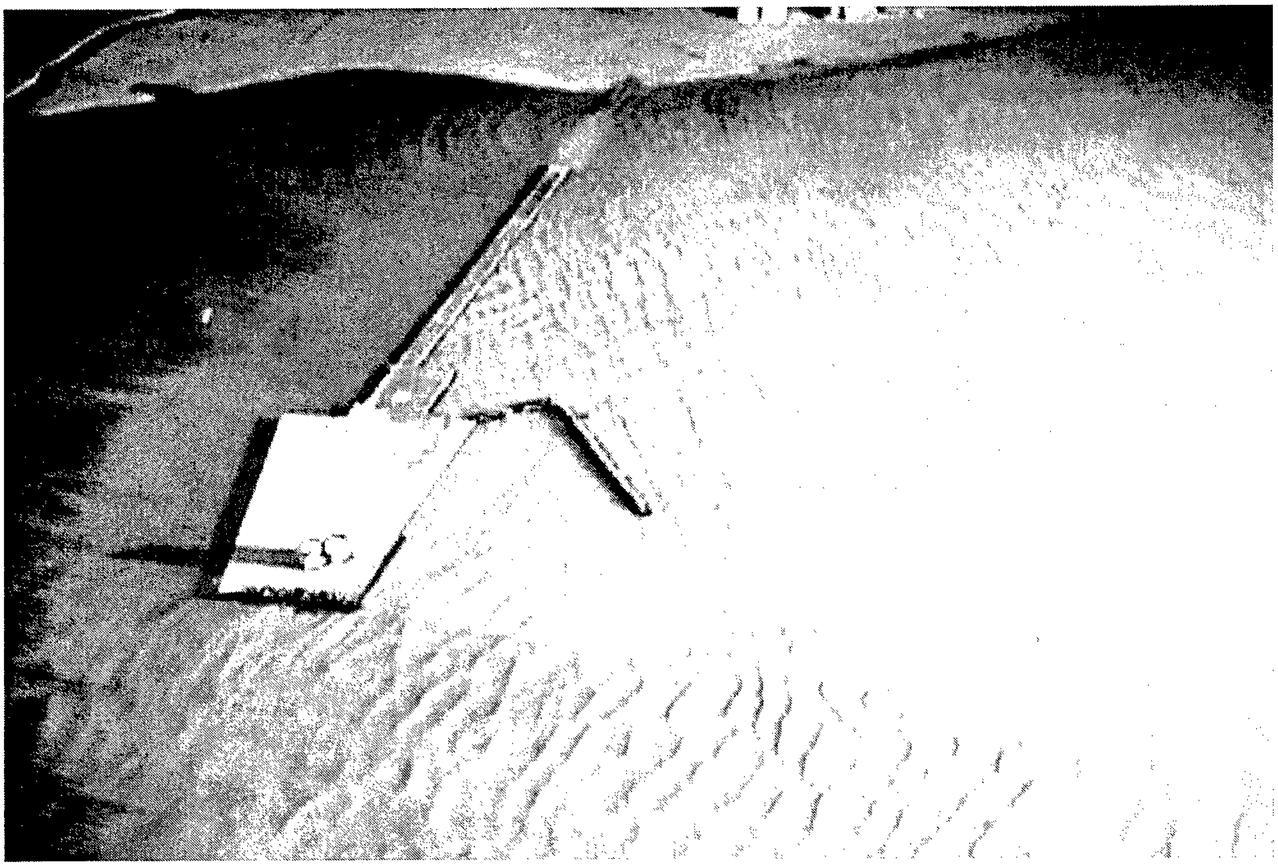


Photo 29. Typical wave patterns for Plan 4; 4.7-sec, 1.2-m (4-ft) waves from 90 deg

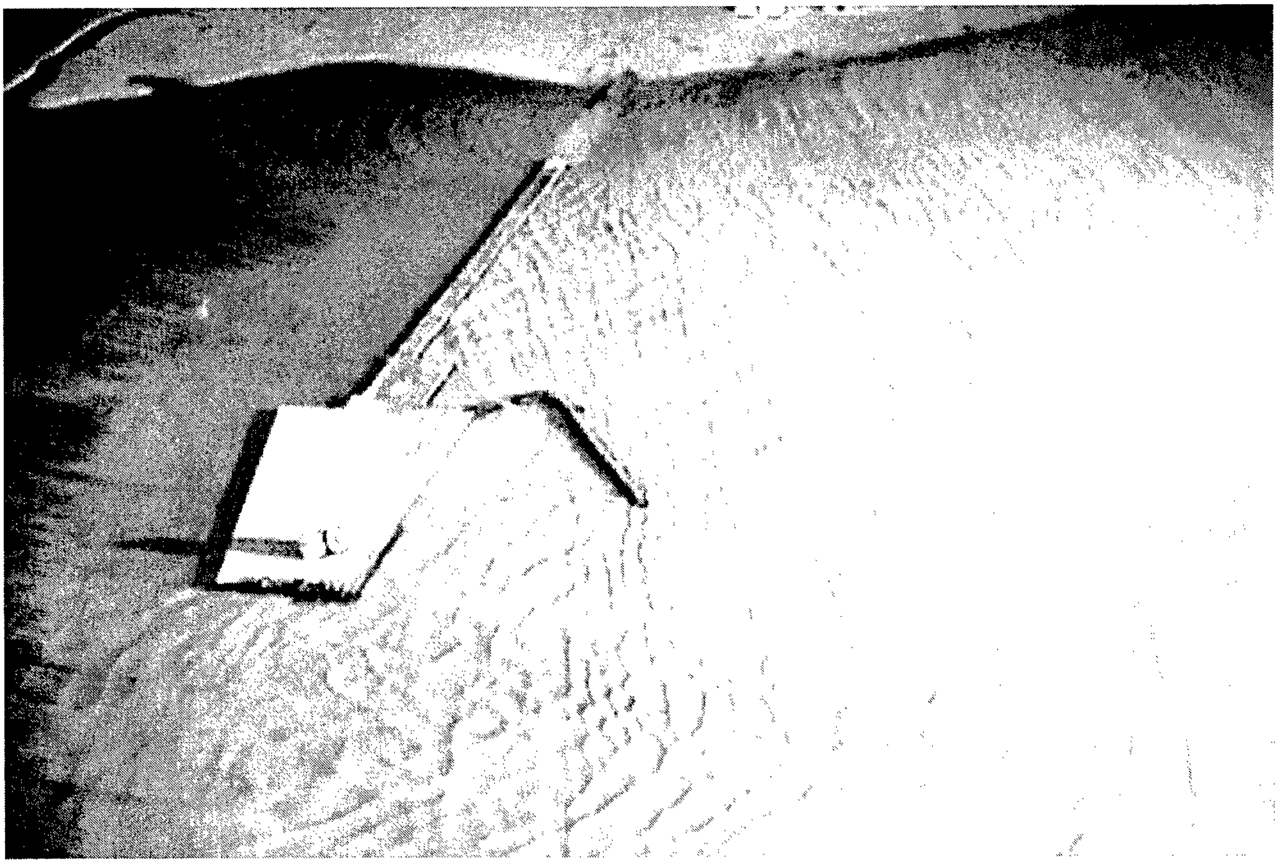


Photo 30. Typical wave patterns for Plan 4; 5.7-sec, 2.1-m (7-ft) waves from 90 deg

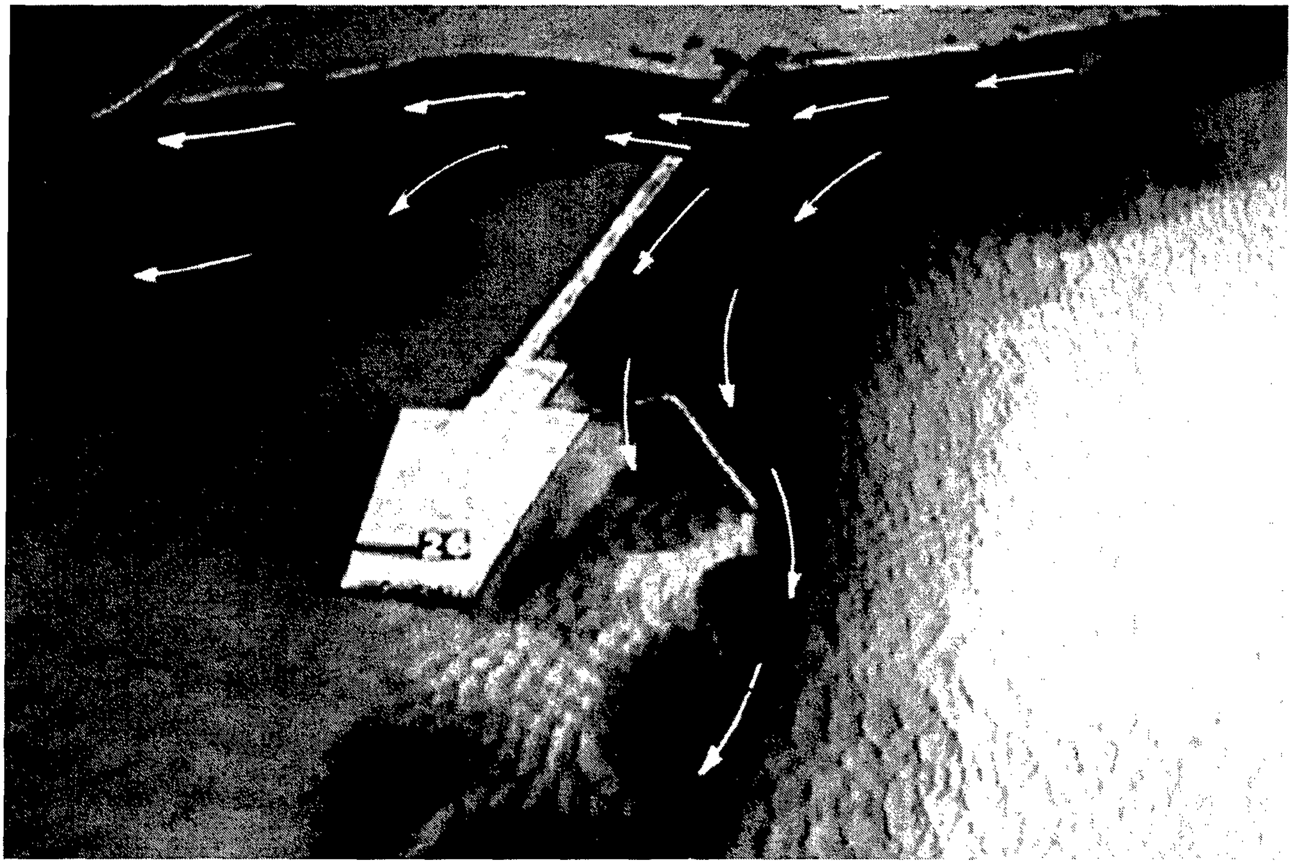


Photo 31. Typical wave and current patterns for Plan 4; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

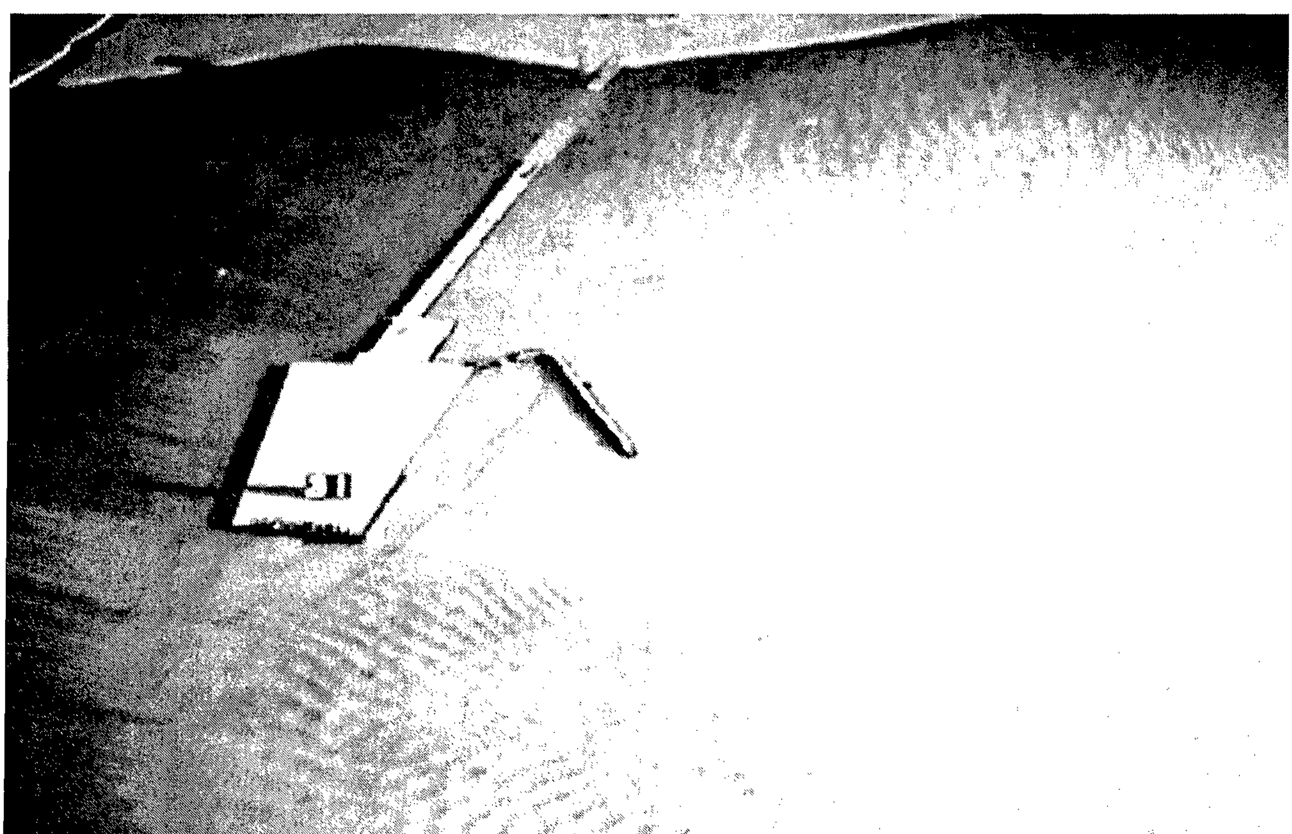


Photo 32. Typical wave patterns for Plan 5; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

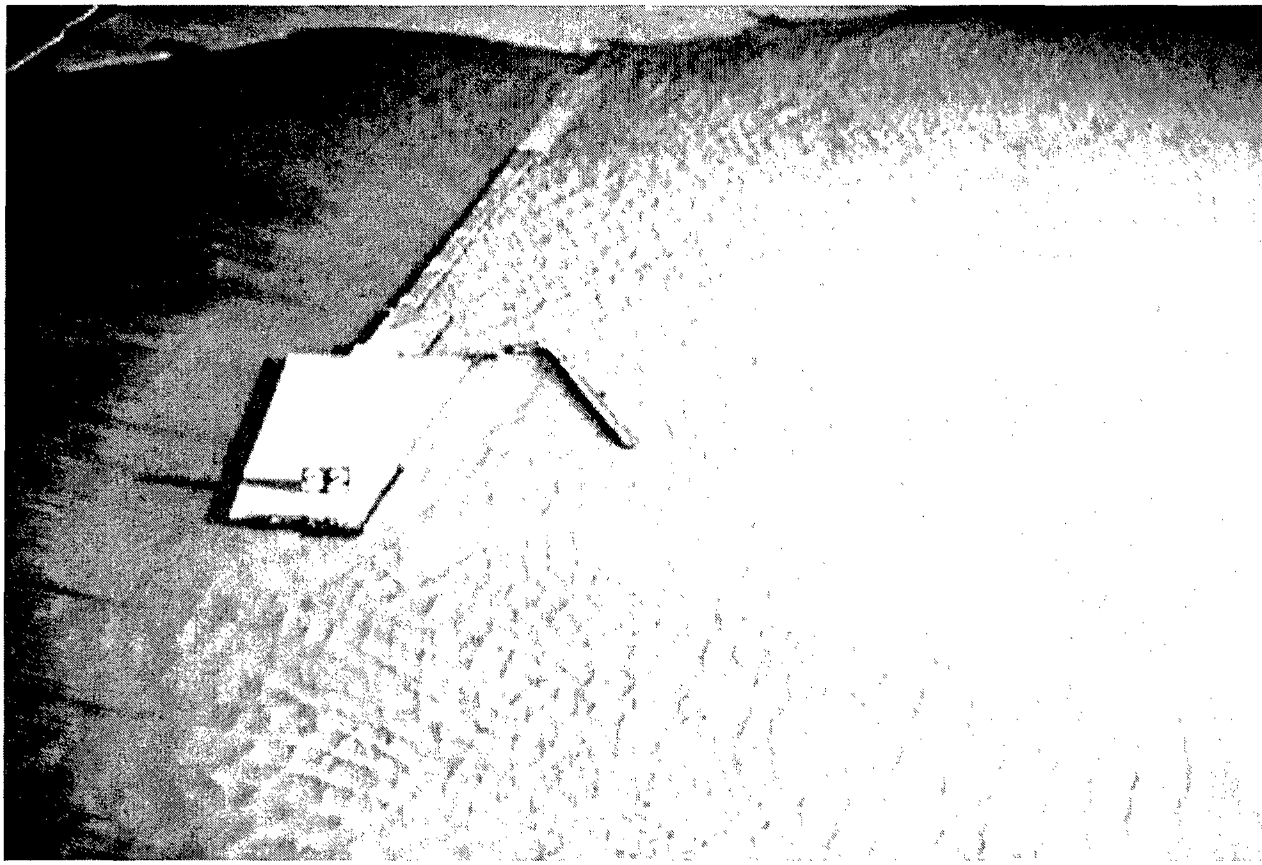


Photo 33. Typical wave patterns for Plan 5; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

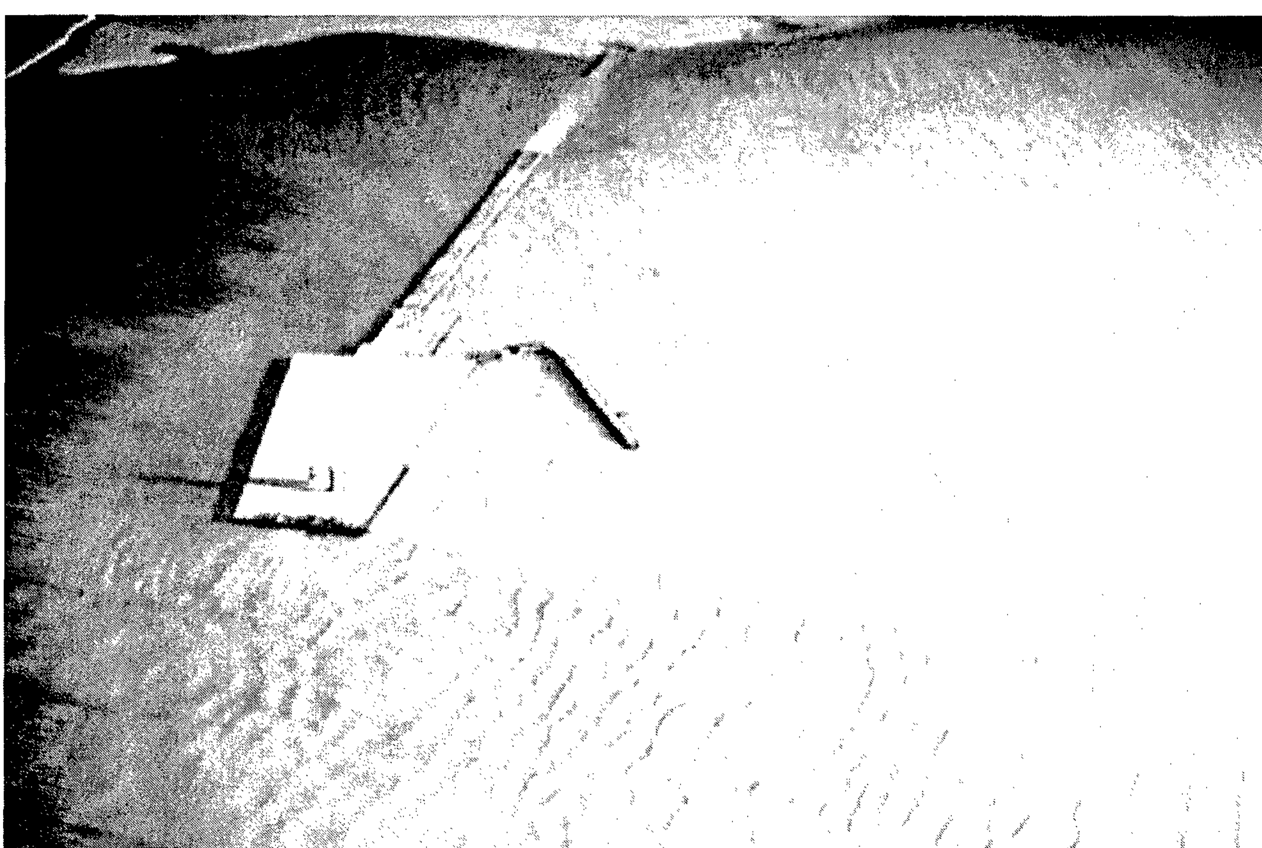


Photo 34. Typical wave patterns for Plan 5; 4.7-sec, 1.2-m (4-ft) waves from 90 deg

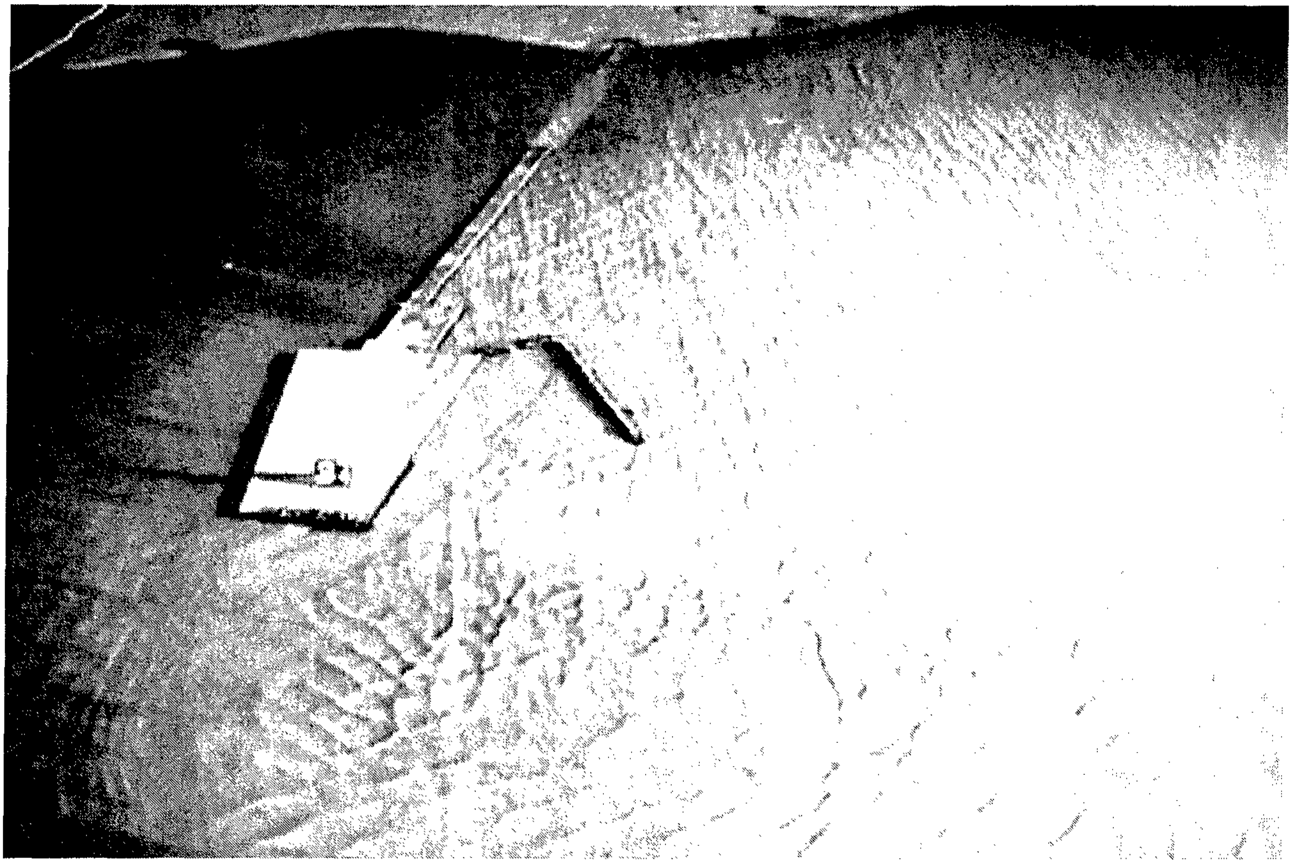


Photo 35. Typical wave patterns for Plan 5; 5.7-sec, 2.1-m (7-ft) waves from 90 deg

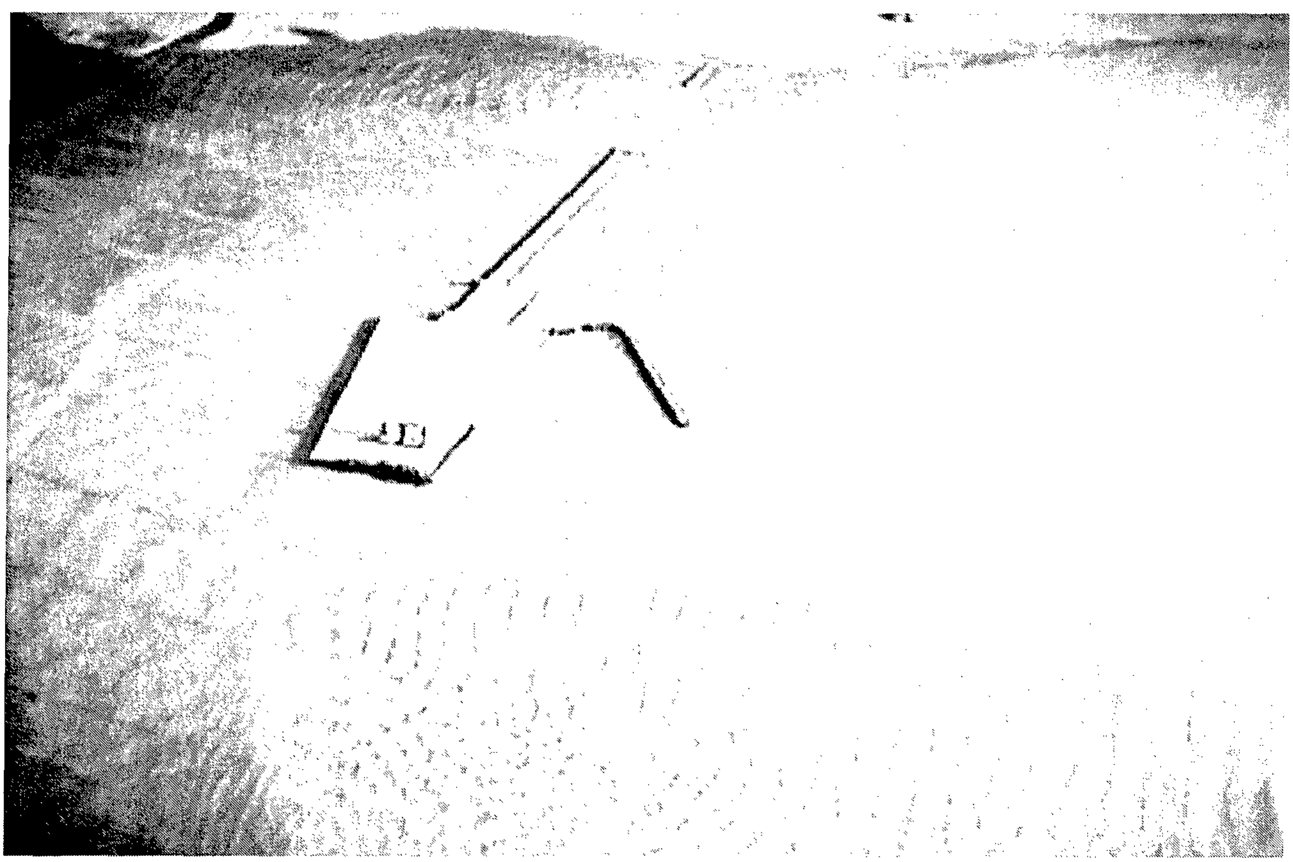


Photo 36. Typical wave patterns for Plan 5; 2.7-sec, 0.4-m (1.3-ft) waves from 110 deg

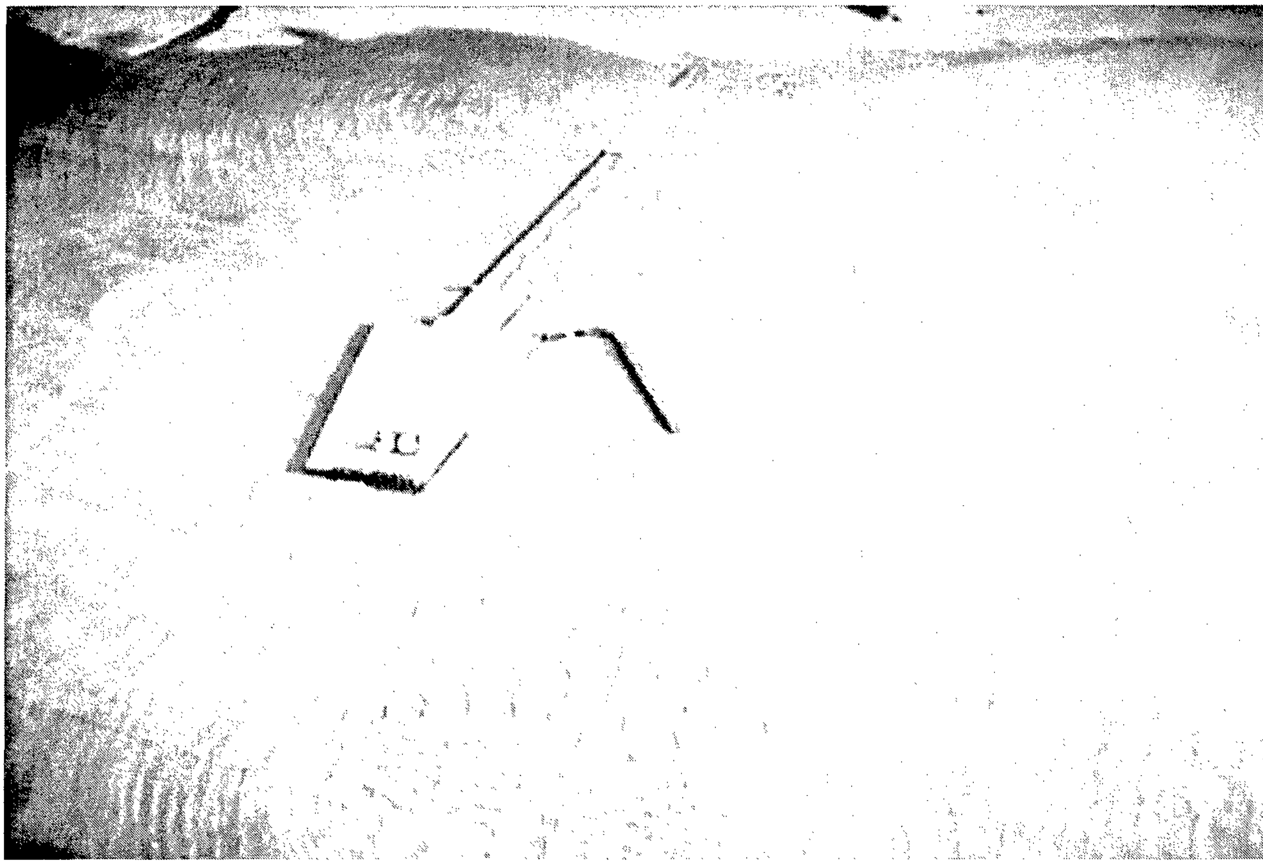


Photo 37. Typical wave patterns for Plan 5; 3.2-sec, 0.55-m (1.8-ft) waves from 110 deg

Photo 38. Typical wave patterns for Plan 5; 4.7-sec, 1.2-m (4-ft) waves from 110 deg

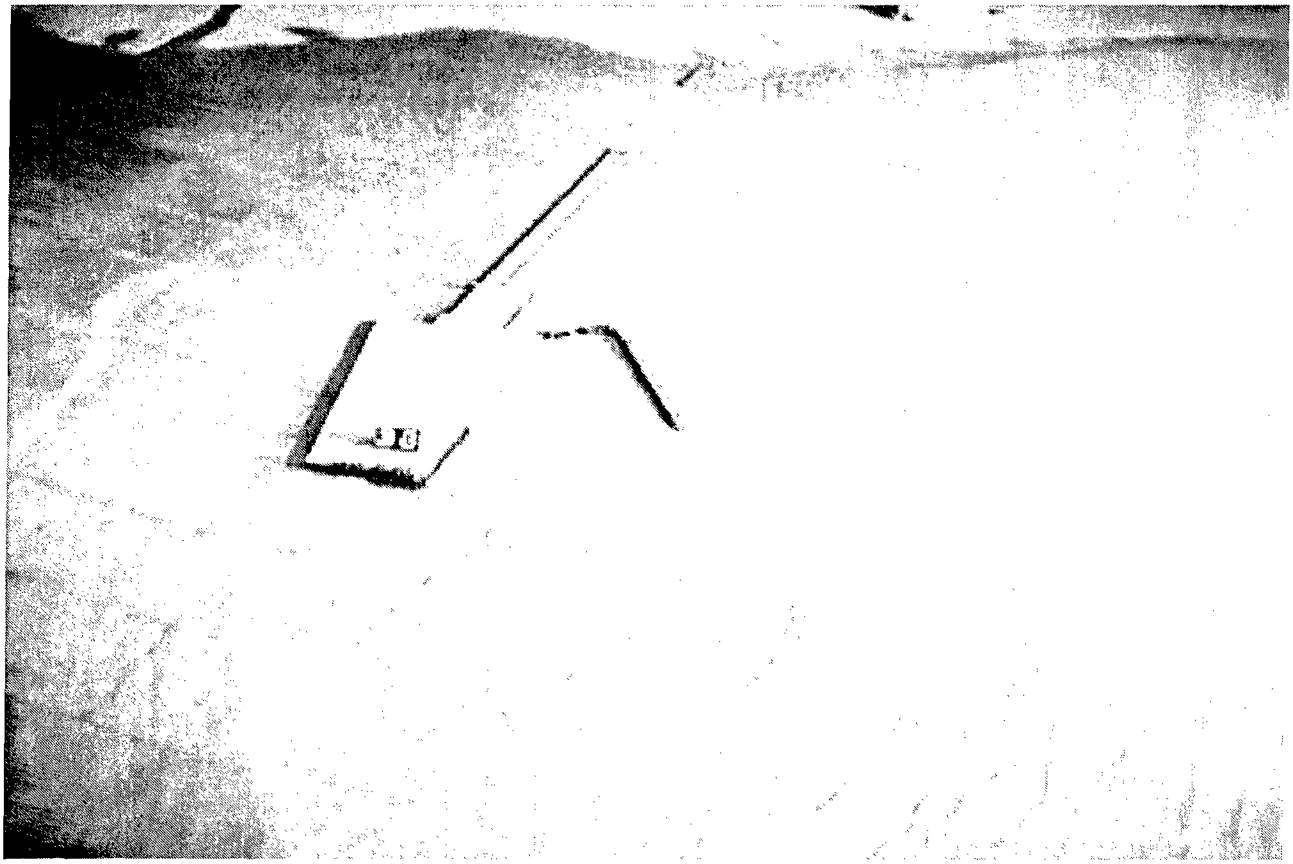


Photo 39. Typical wave patterns for Plan 5; 5.7-sec, 2.1-m (7-ft) waves from 110 deg

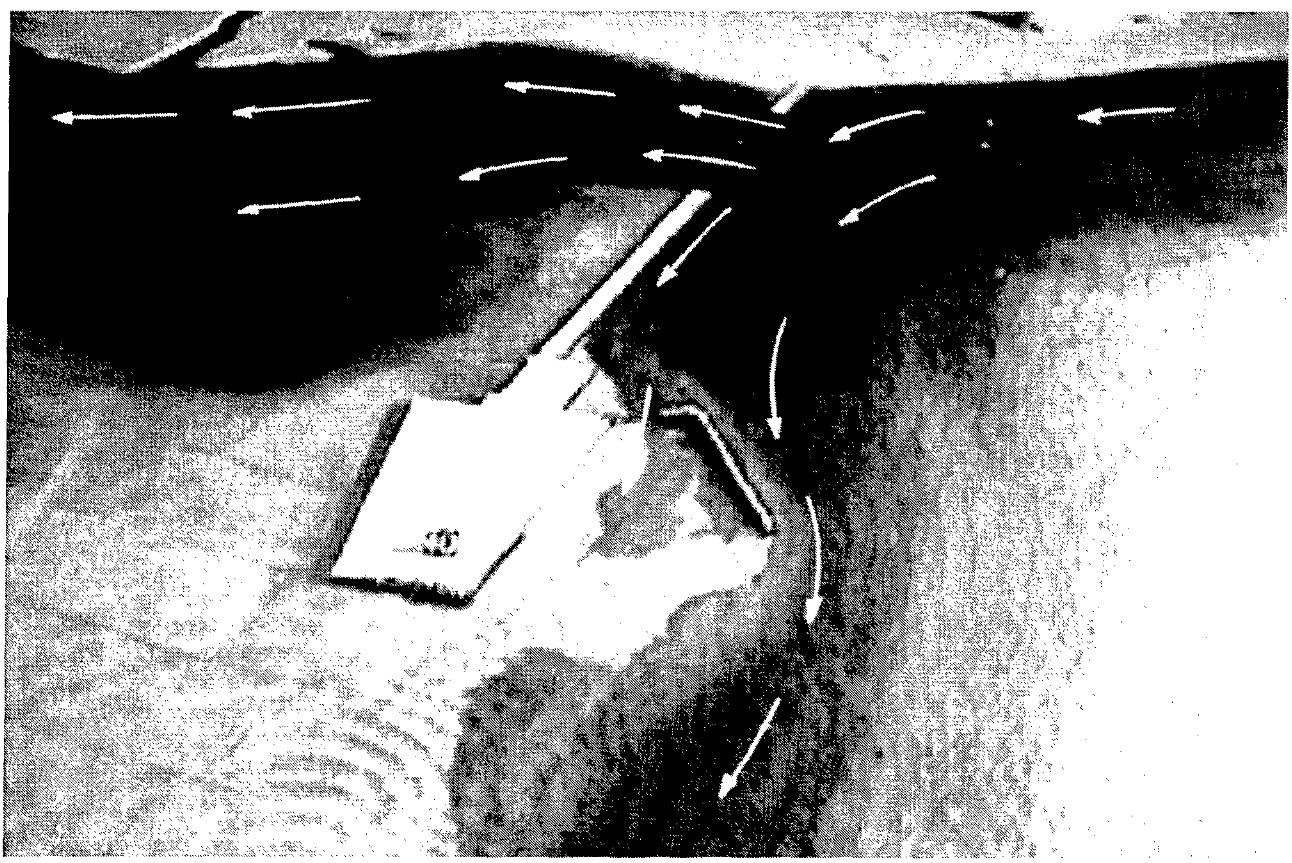


Photo 40. Typical wave and current patterns for Plan 5; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

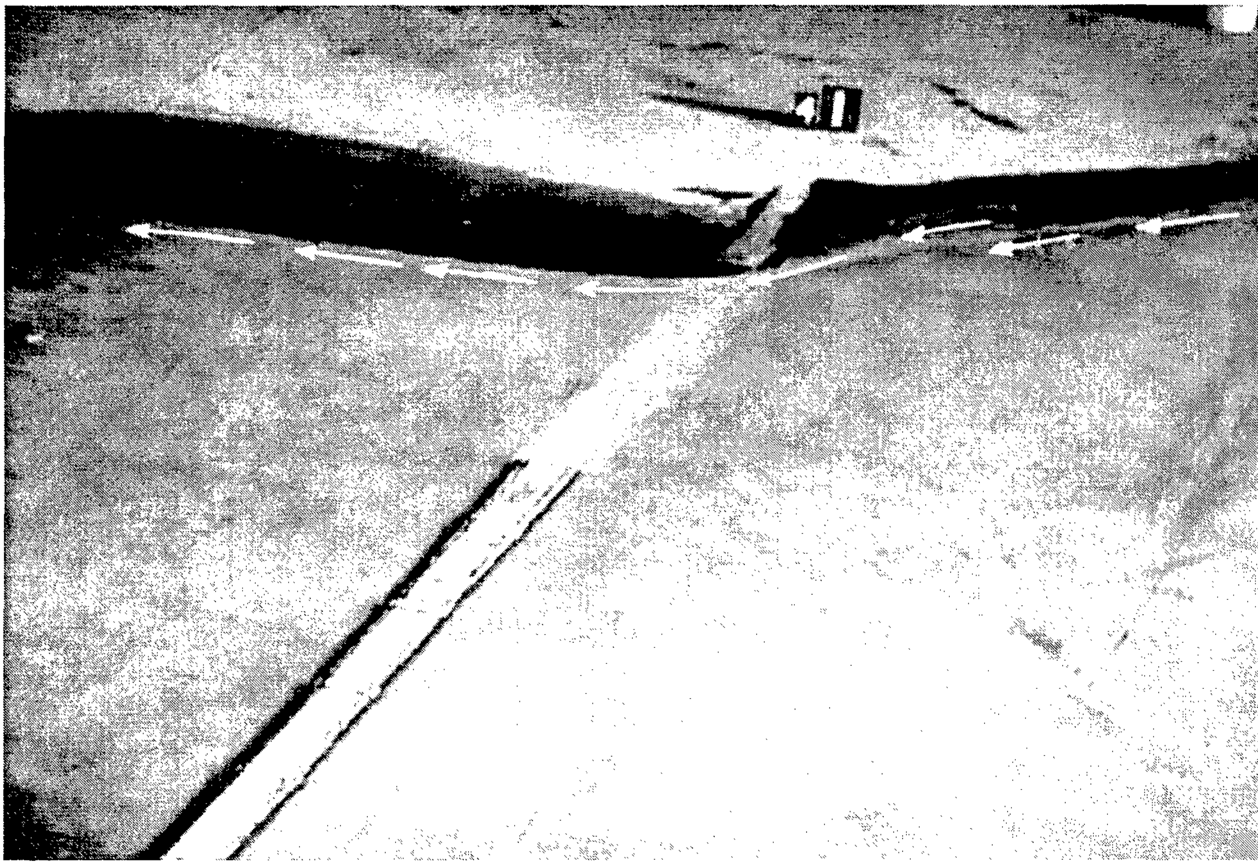


Photo 41. General movement of tracer material and subsequent deposits for Plan 5; 3.2-sec, 0.55-m (1.8-ft) waves from 90 deg

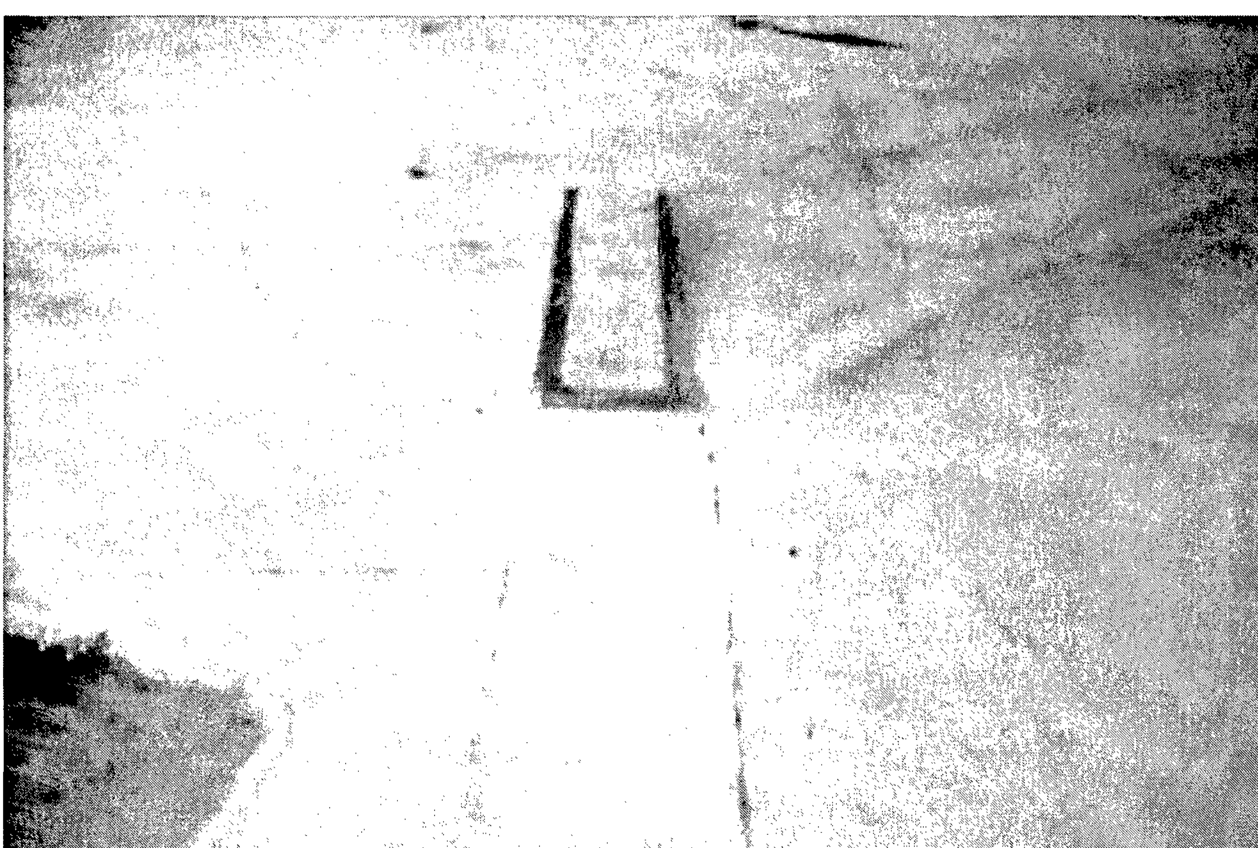


Photo 42. View of inner portion of causeway for Plans 4 and 5

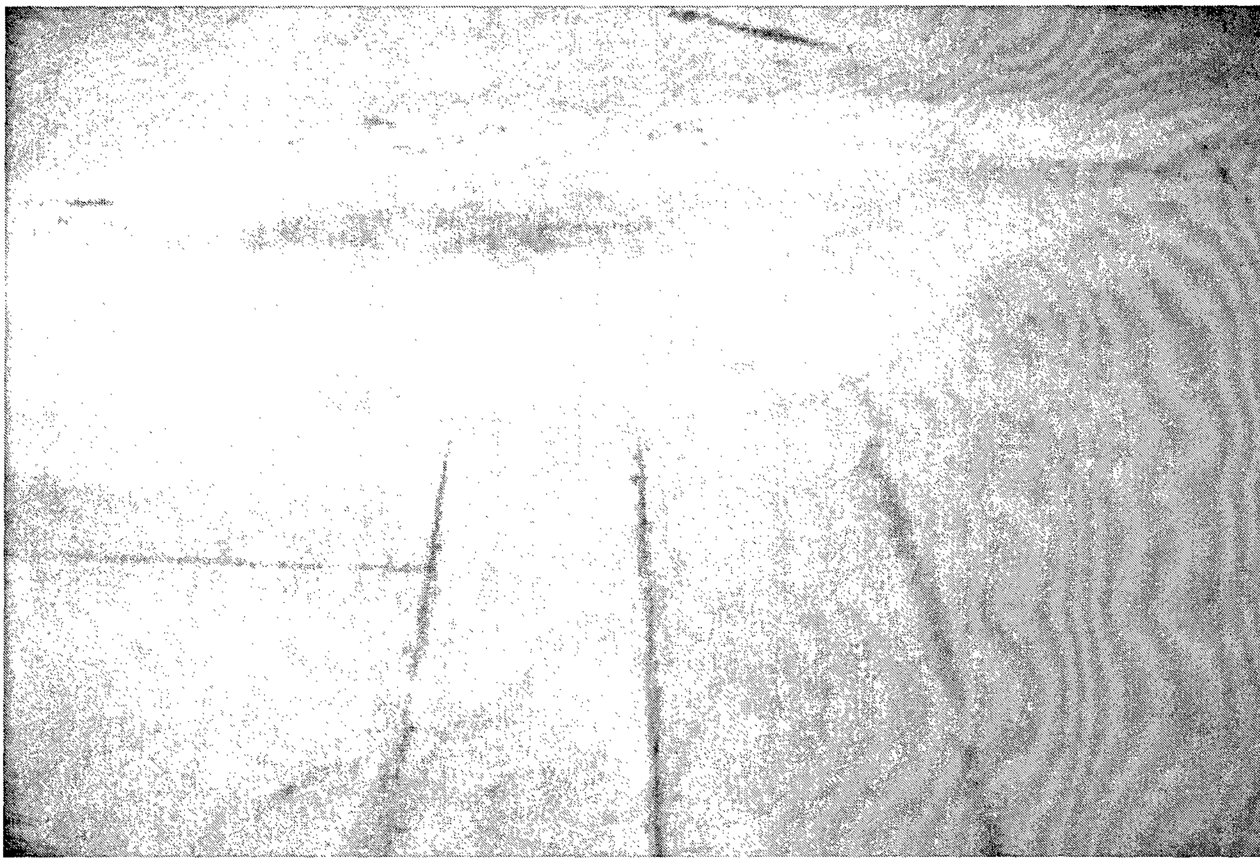


Photo 43. View of shoreline for Plan 6 after removal of inner portion of causeway

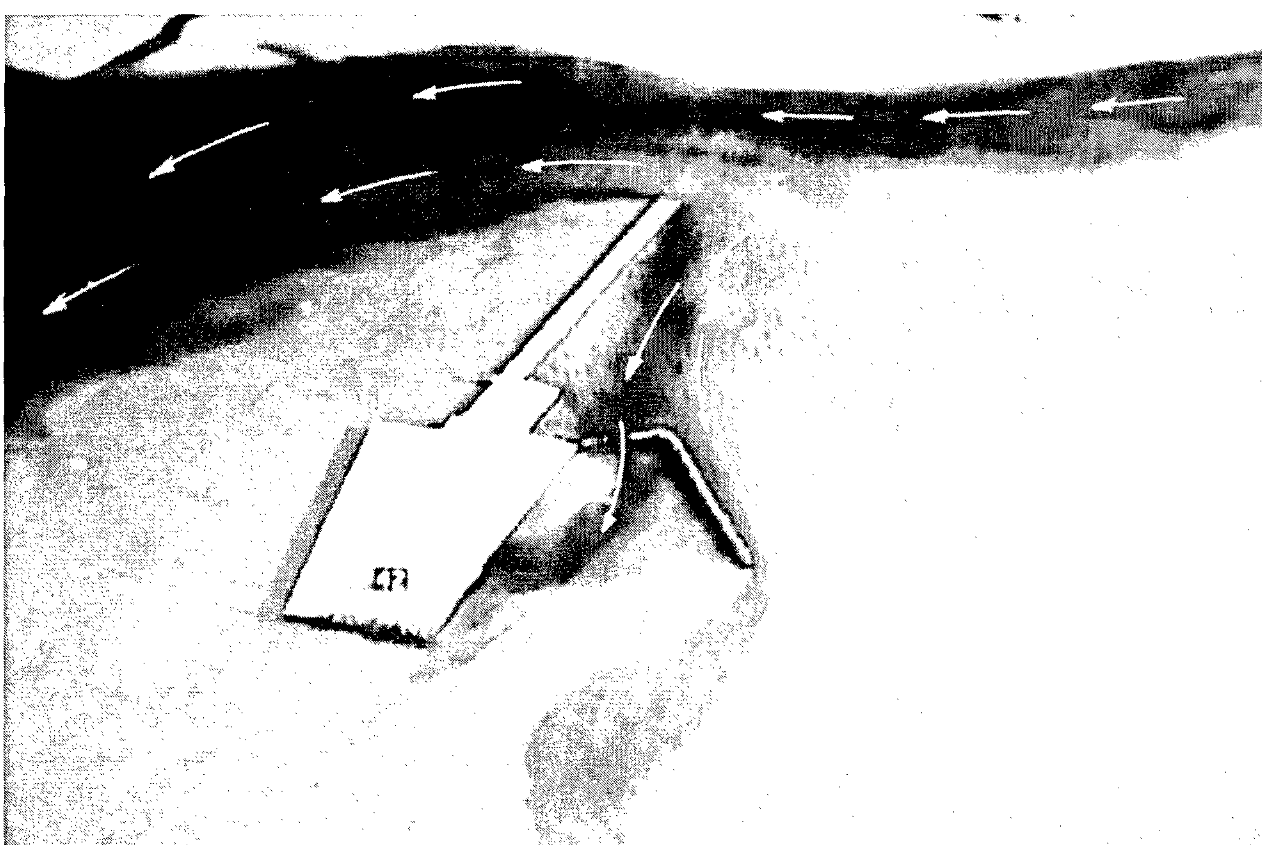


Photo 44. Typical wave and current patterns for Plan 6; 2.7-sec, 0.4-m (1.3-ft) waves from 90 deg

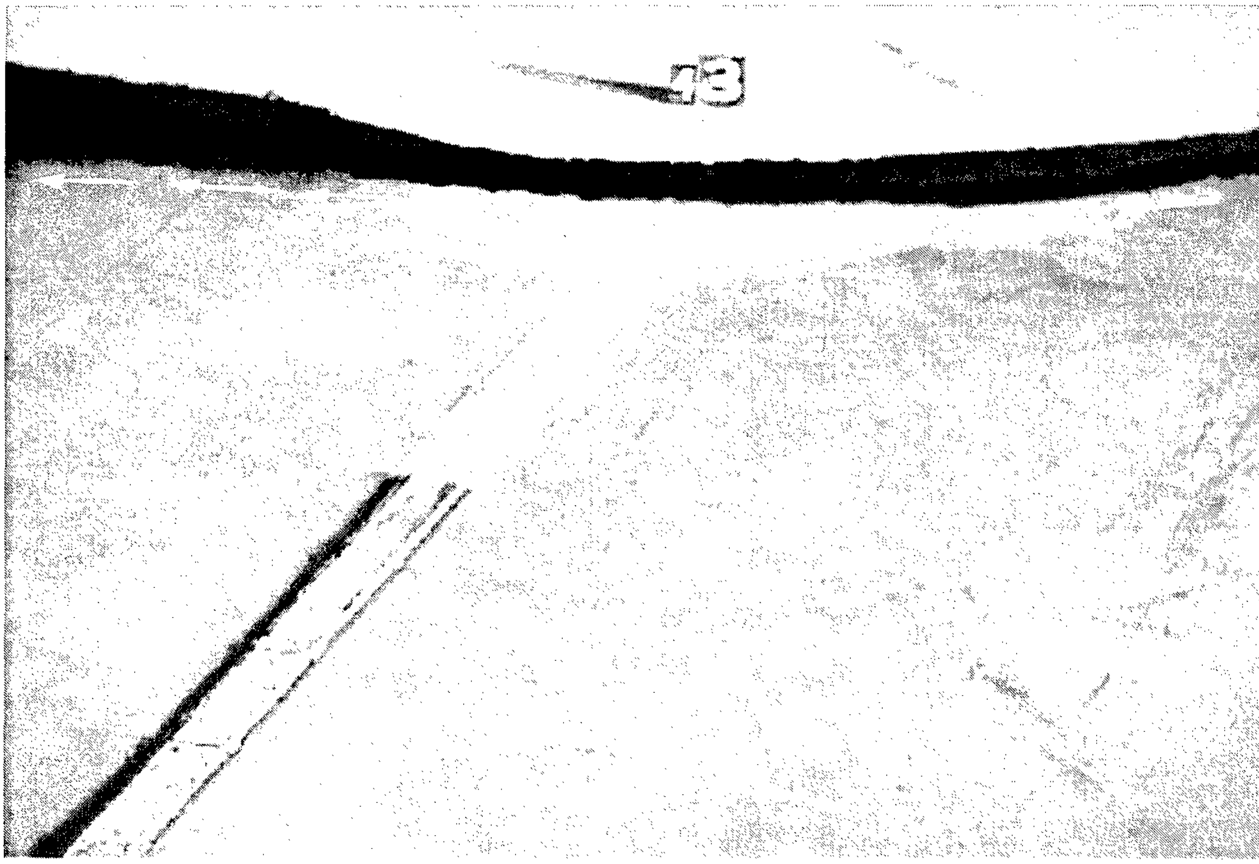
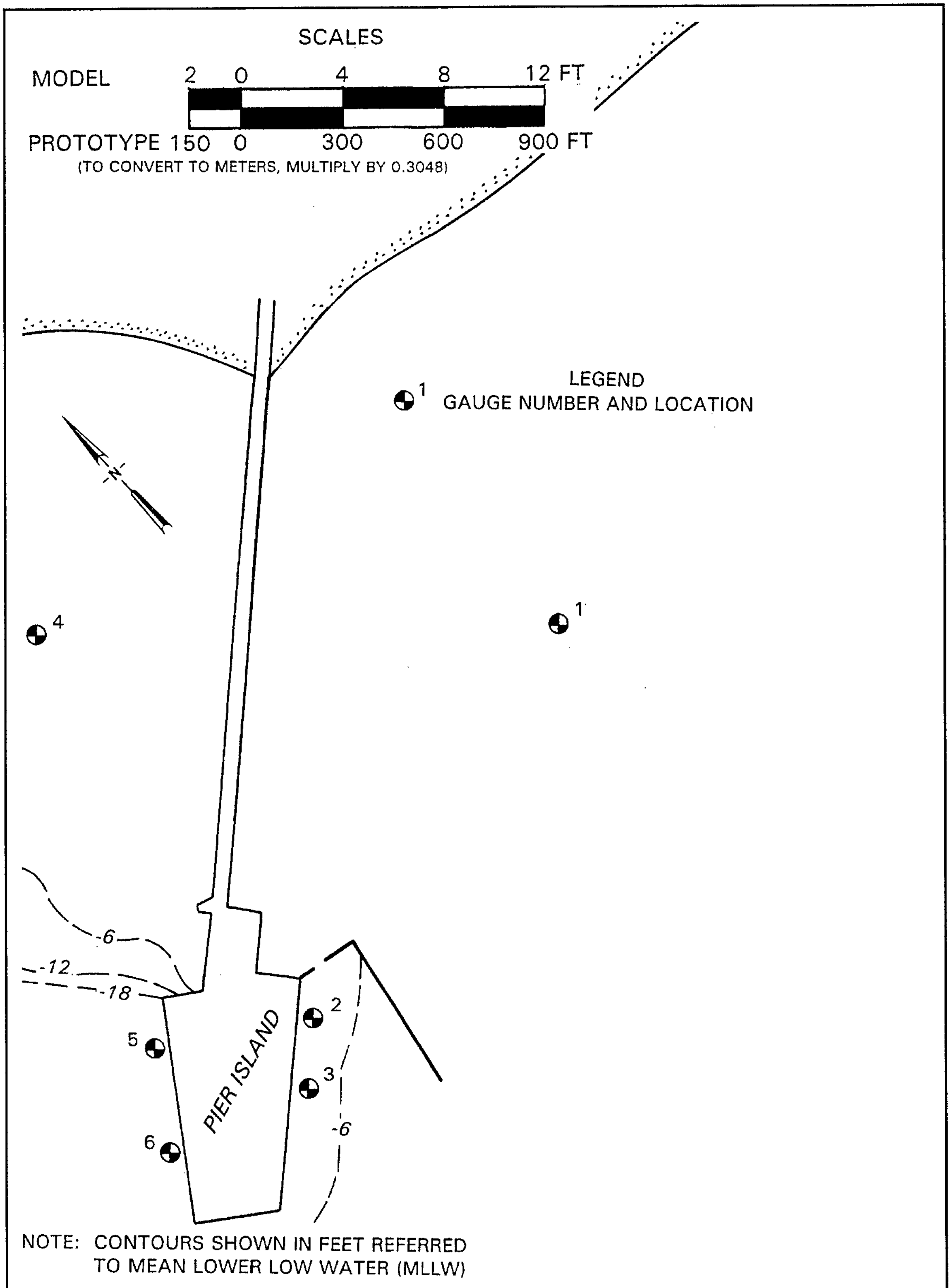
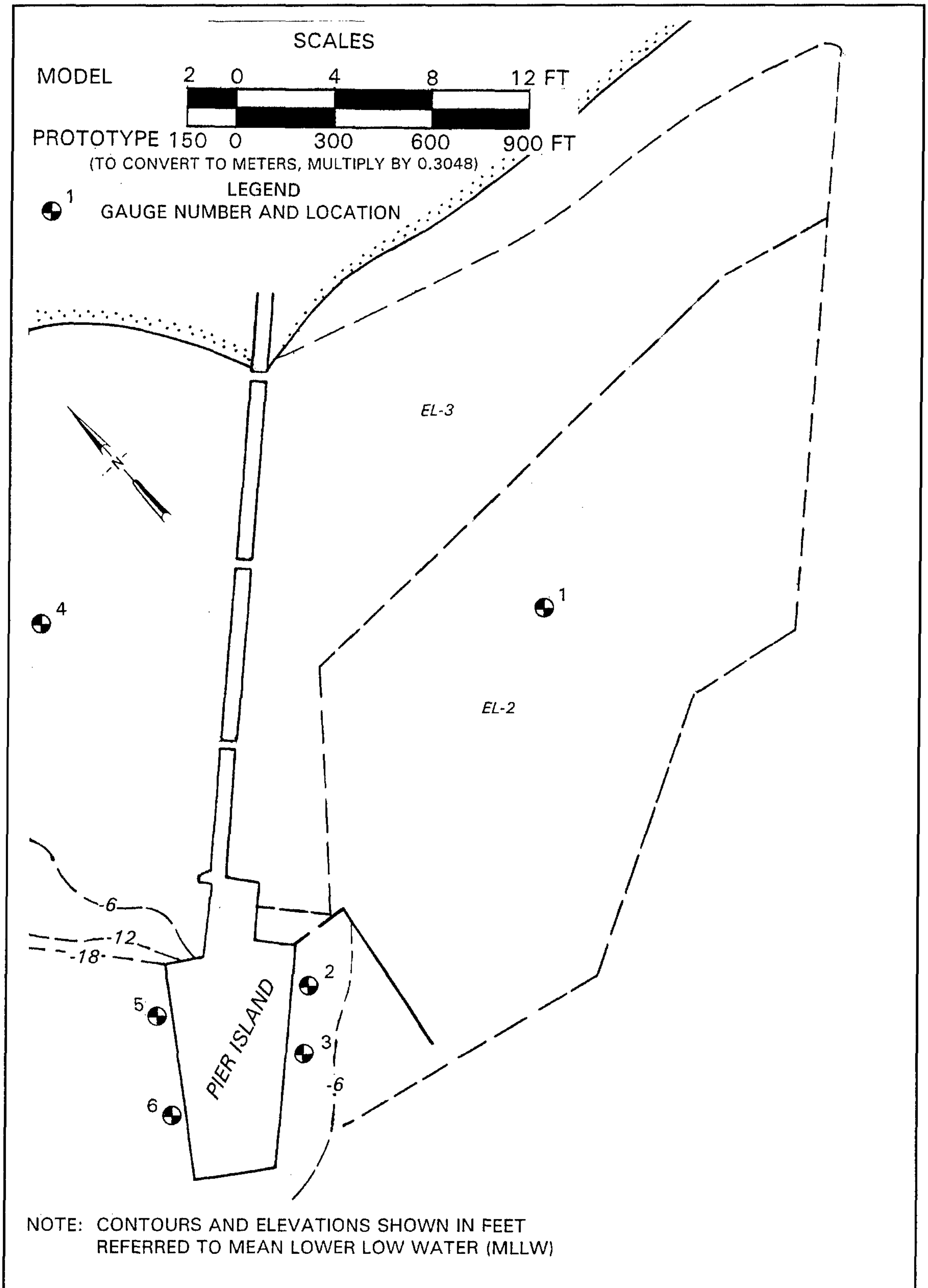


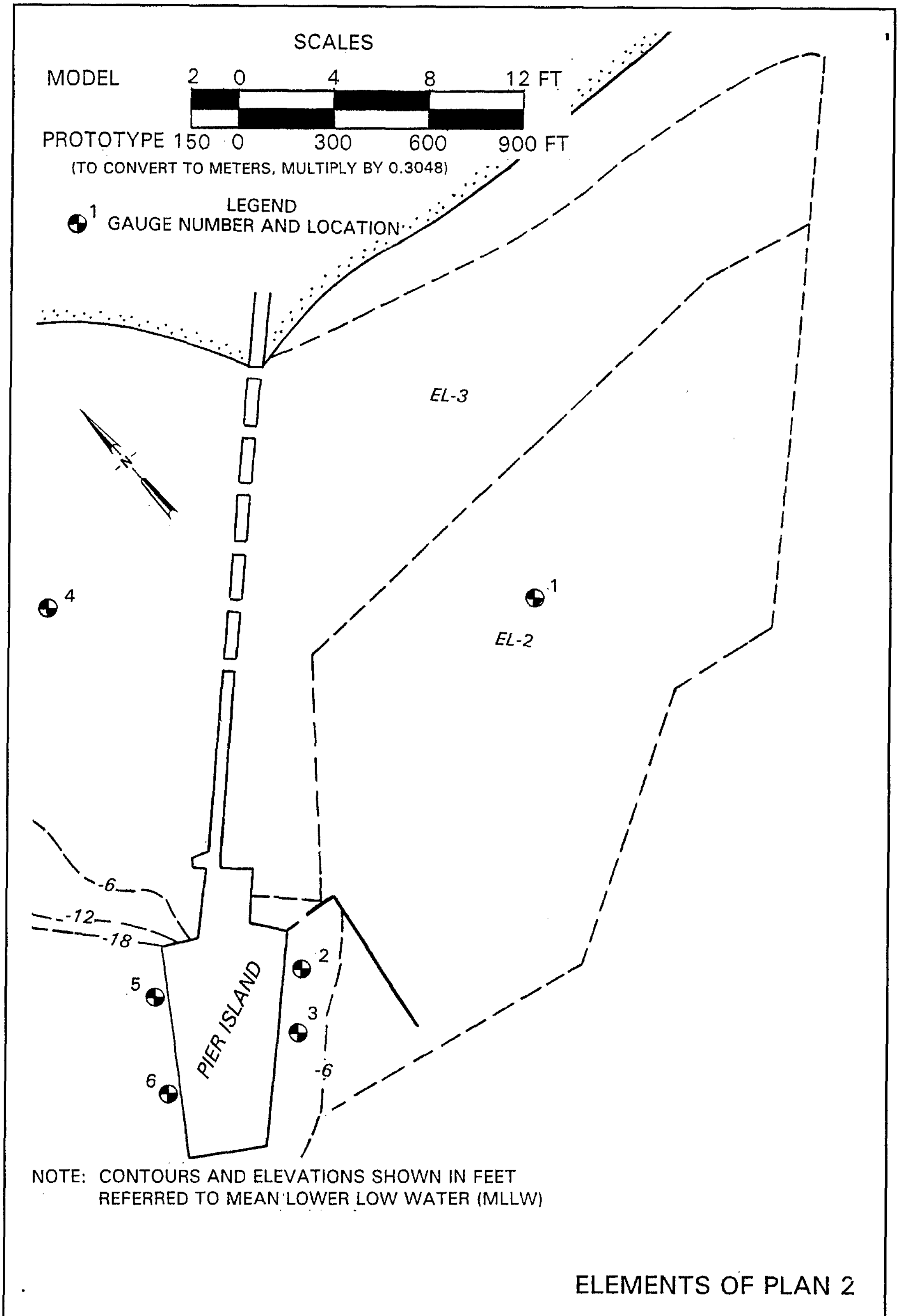
Photo 45. General movement of tracer material and subsequent deposits for Plan 6; 3.2-sec, 0.55-m(1.8-ft) waves from 90 deg



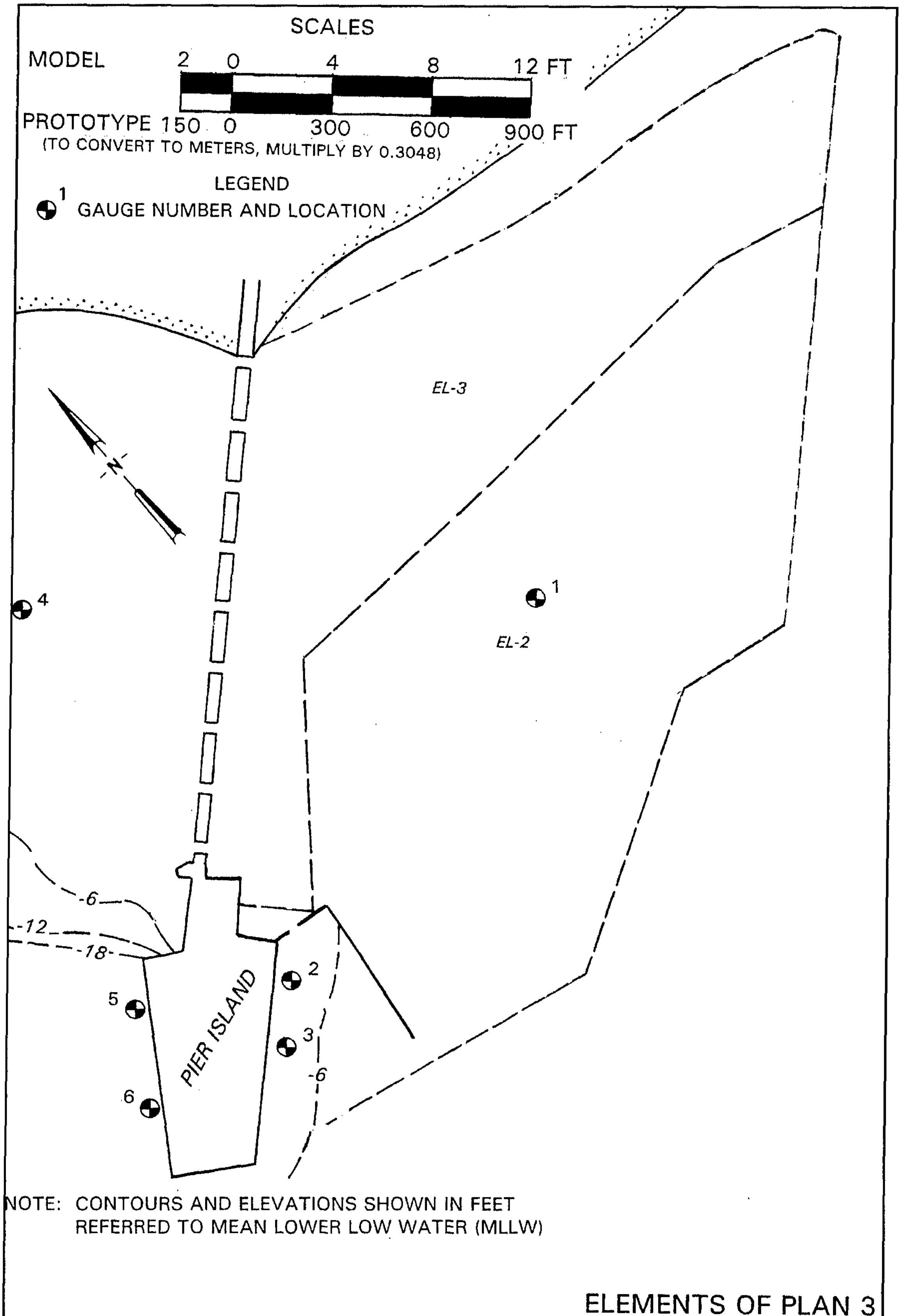
EXISTING CONDITIONS



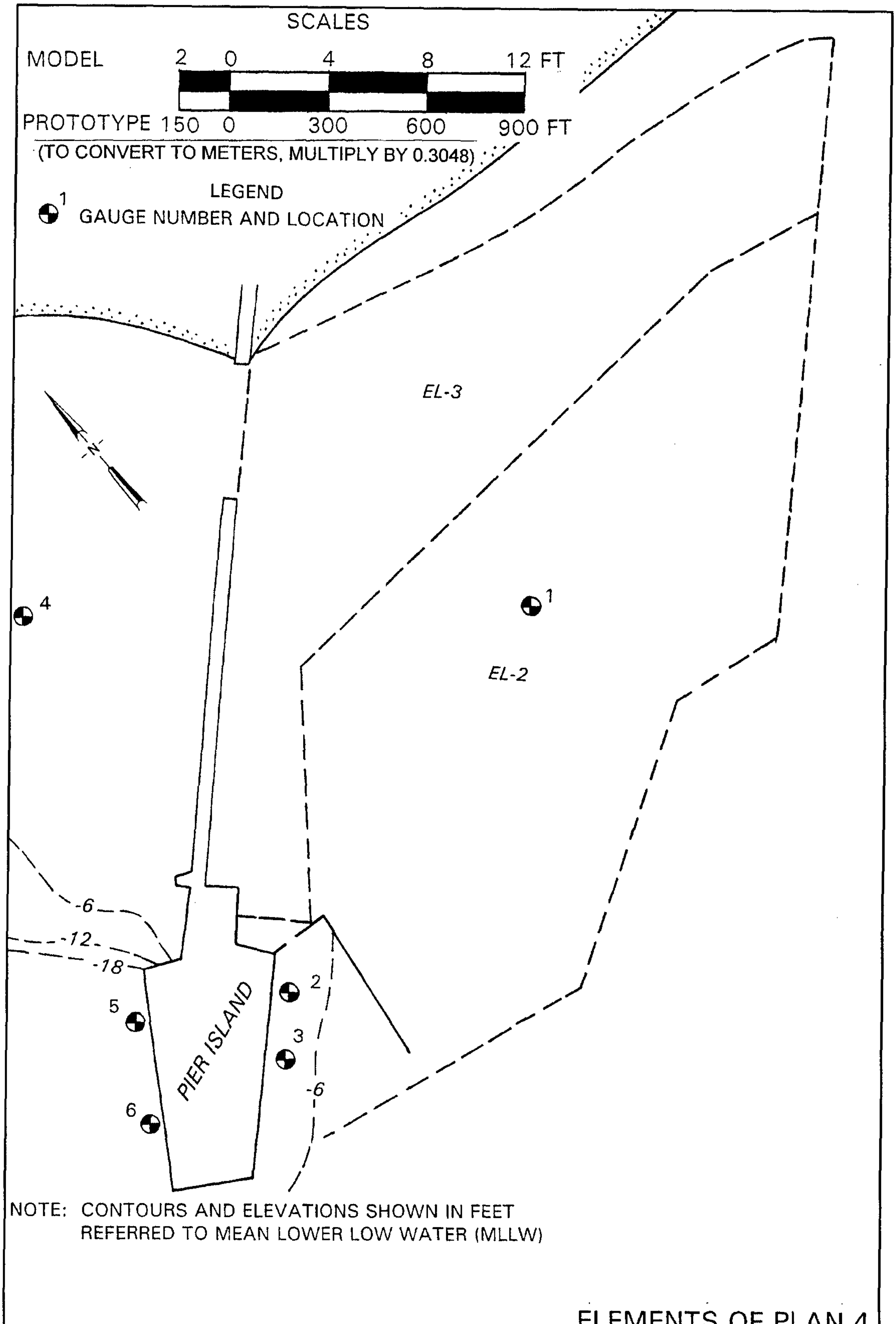
ELEMENTS OF PLAN 1



ELEMENTS OF PLAN 2

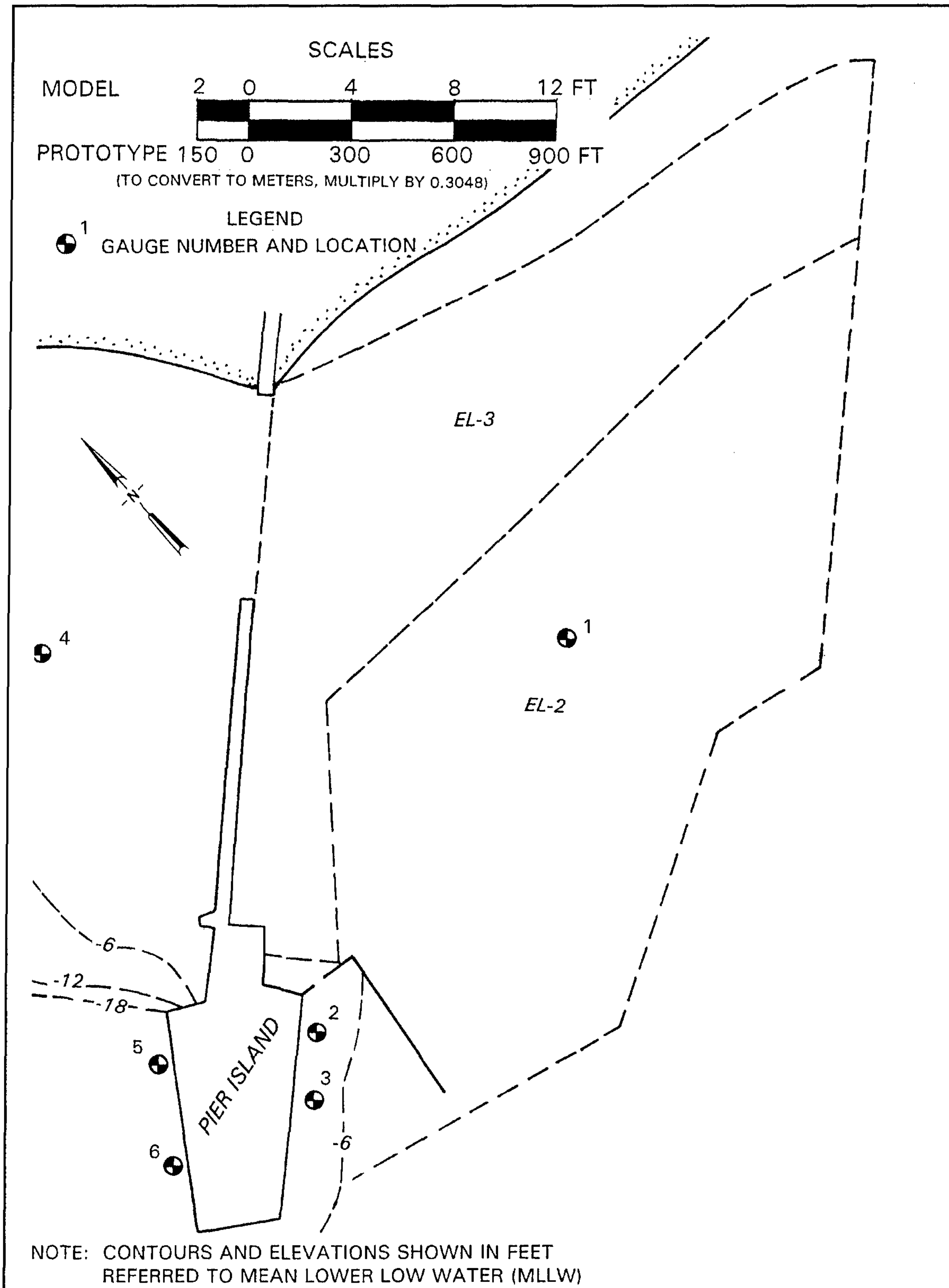


ELEMENTS OF PLAN 3

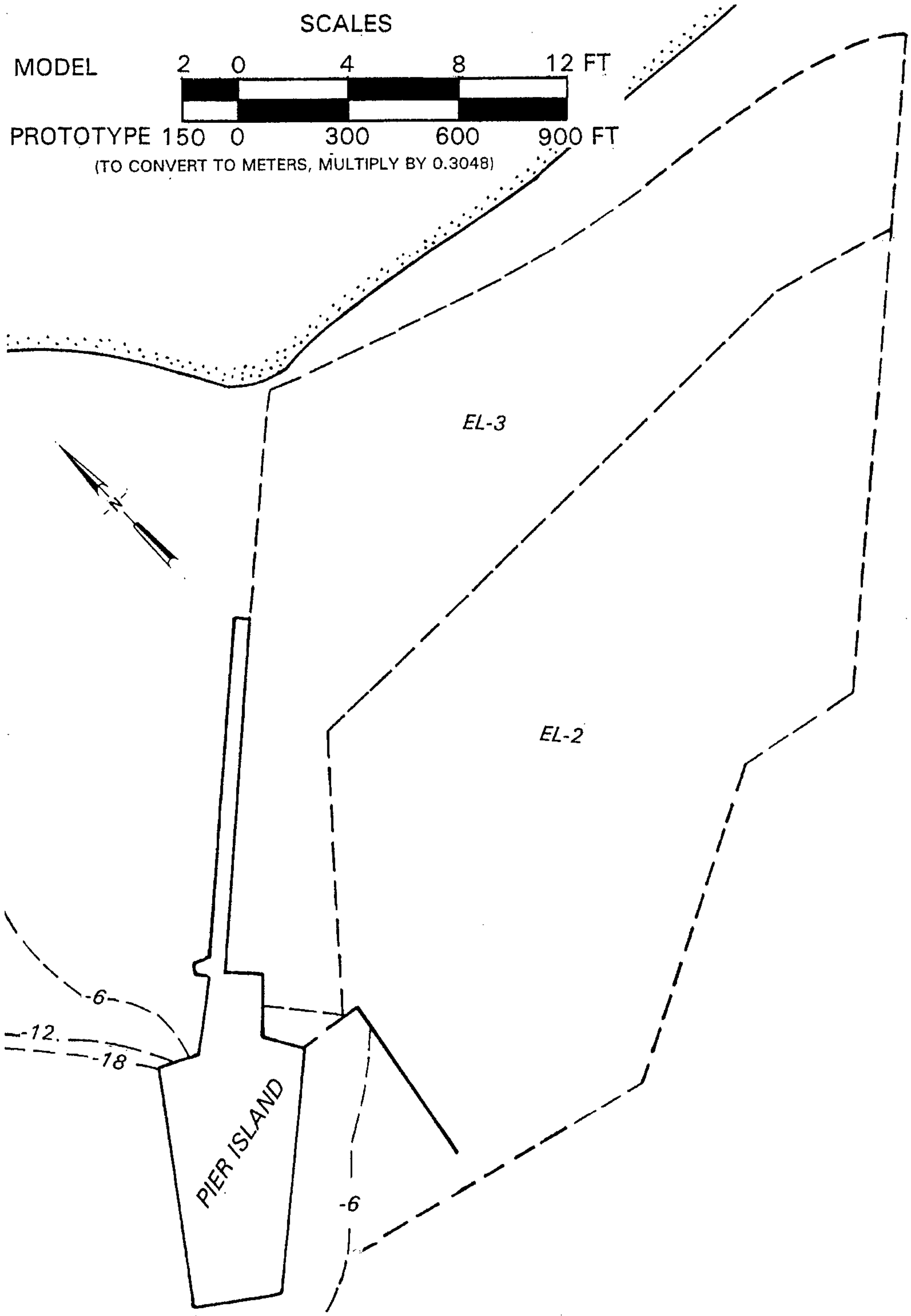


ELEMENTS OF PLAN 4

Plate 5

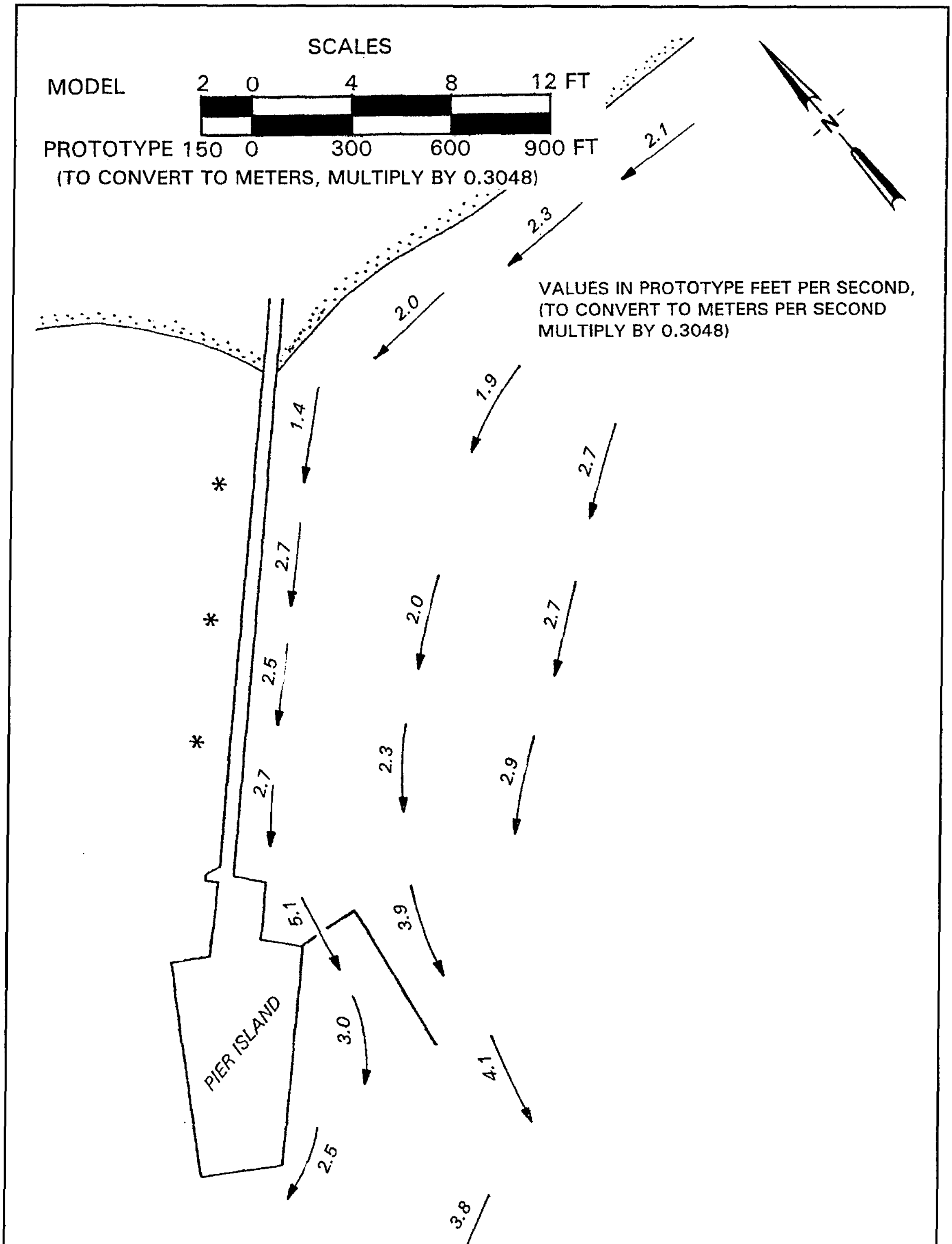


ELEMENTS OF PLAN 5



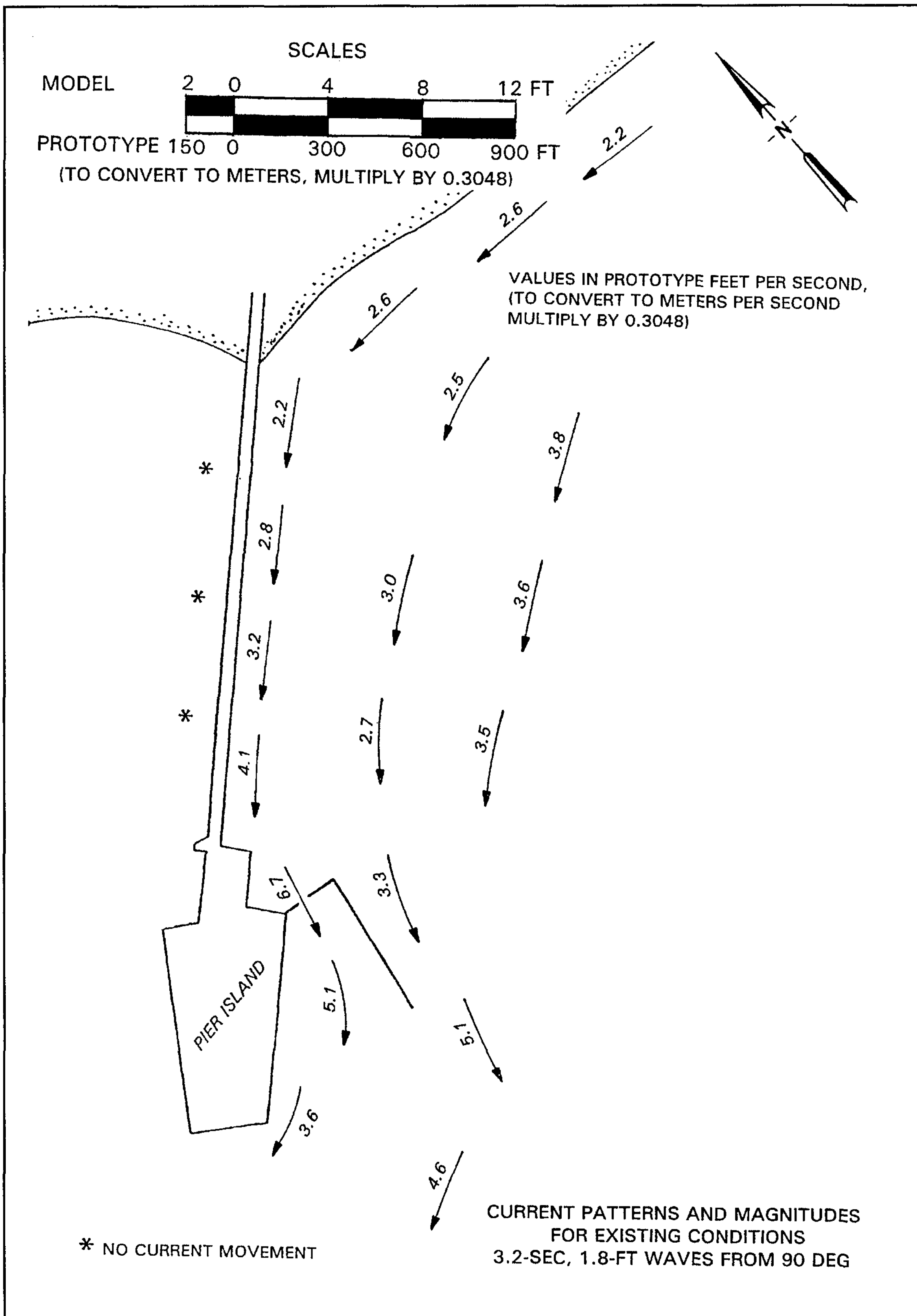
NOTE: CONTOURS AND ELEVATIONS SHOWN IN FEET REFERRED TO MEAN LOWER LOW WATER (MLLW)

ELEMENTS OF PLAN 6



CURRENT PATTERNS AND MAGNITUDES
FOR EXISTING CONDITIONS
2.7-SEC, 1.3-FT WAVES FROM 90 DEG

Plate 8



CURRENT PATTERNS AND MAGNITUDES
FOR EXISTING CONDITIONS
3.2-SEC, 1.8-FT WAVES FROM 90 DEG

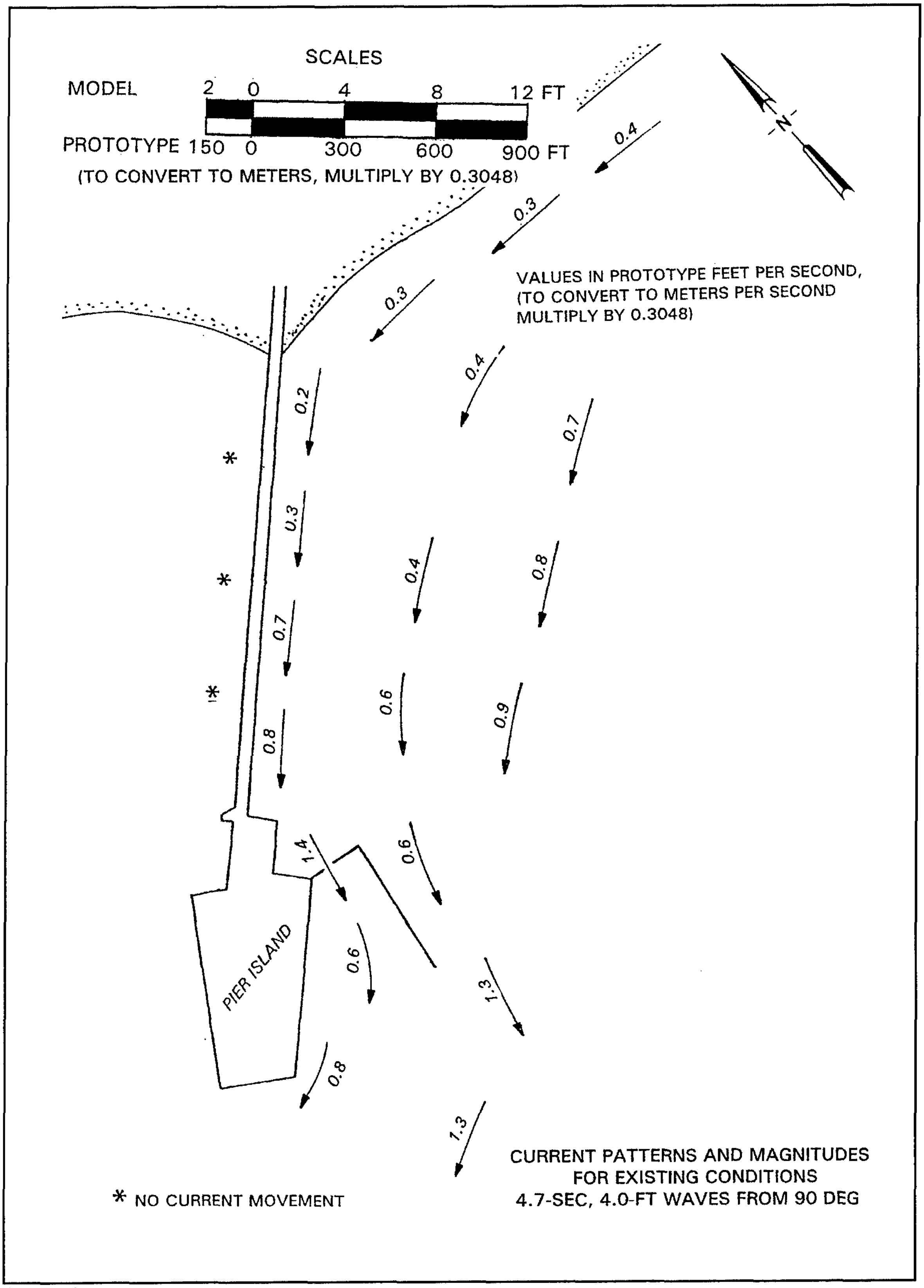

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
N
0.4
0.3
0.3
0.4
0.2
0.7
0.3
0.4
0.8
0.7
0.6
0.9
0.8
1.4
0.6
PIER ISLAND
0.6
1.3
0.8
1.3
* NO CURRENT MOVEMENT
CURRENT PATTERNS AND MAGNITUDES
FOR EXISTING CONDITIONS
4.7-SEC, 4.0-FT WAVES FROM 90 DEG

Plate 10

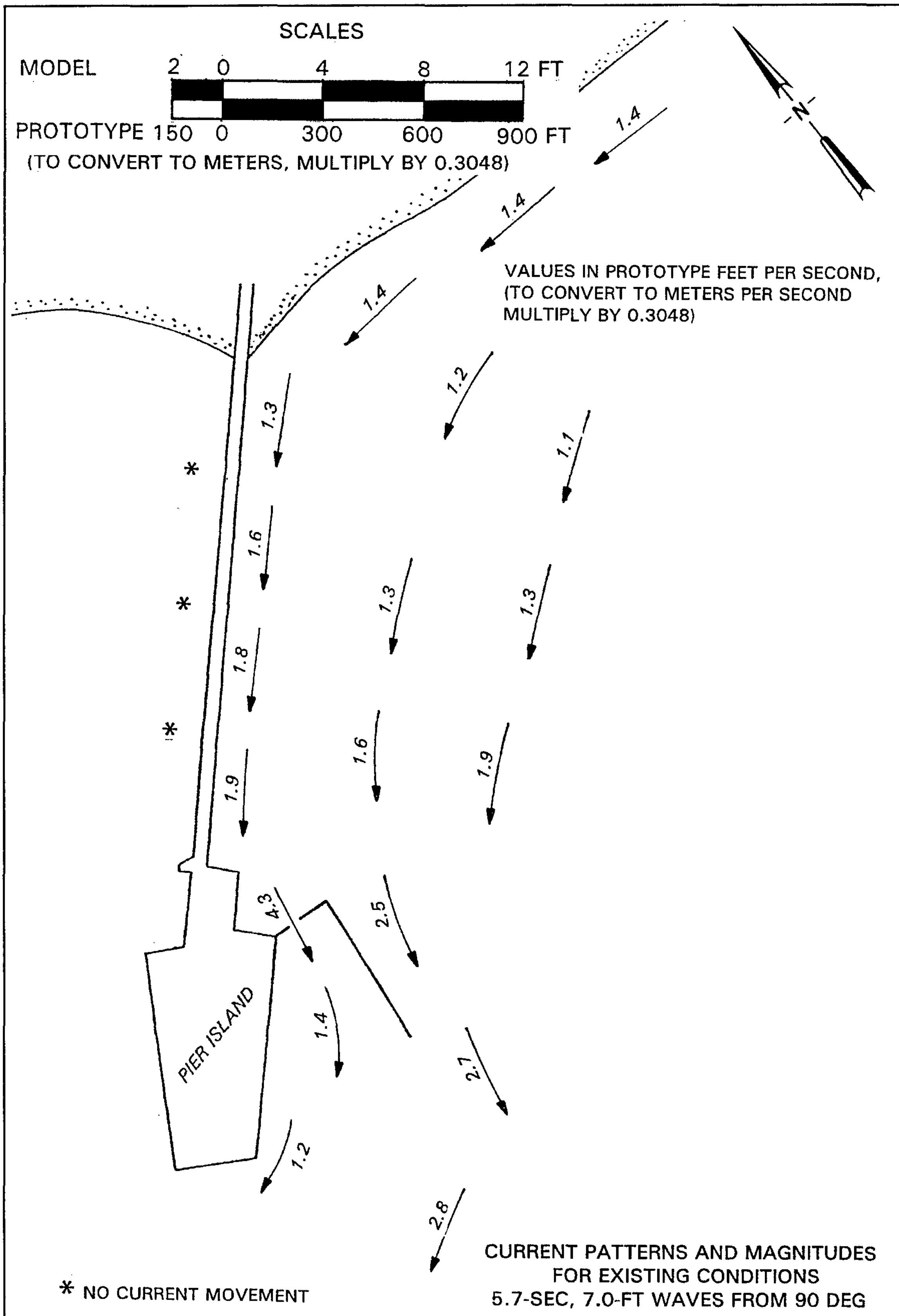

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
VALUES IN PROTOTYPE FEET PER SECOND, (TO CONVERT TO METERS PER SECOND MULTIPLY BY 0.3048)
1.4
1.4
1.4
1.2
1.1
1.3
1.6
1.3
1.3
1.8
1.6
1.9
1.9
4.3
2.5
PIER ISLAND
1.4
2.7
1.2
2.8
* NO CURRENT MOVEMENT
CURRENT PATTERNS AND MAGNITUDES FOR EXISTING CONDITIONS
5.7-SEC, 7.0-FT WAVES FROM 90 DEG

Plate 11

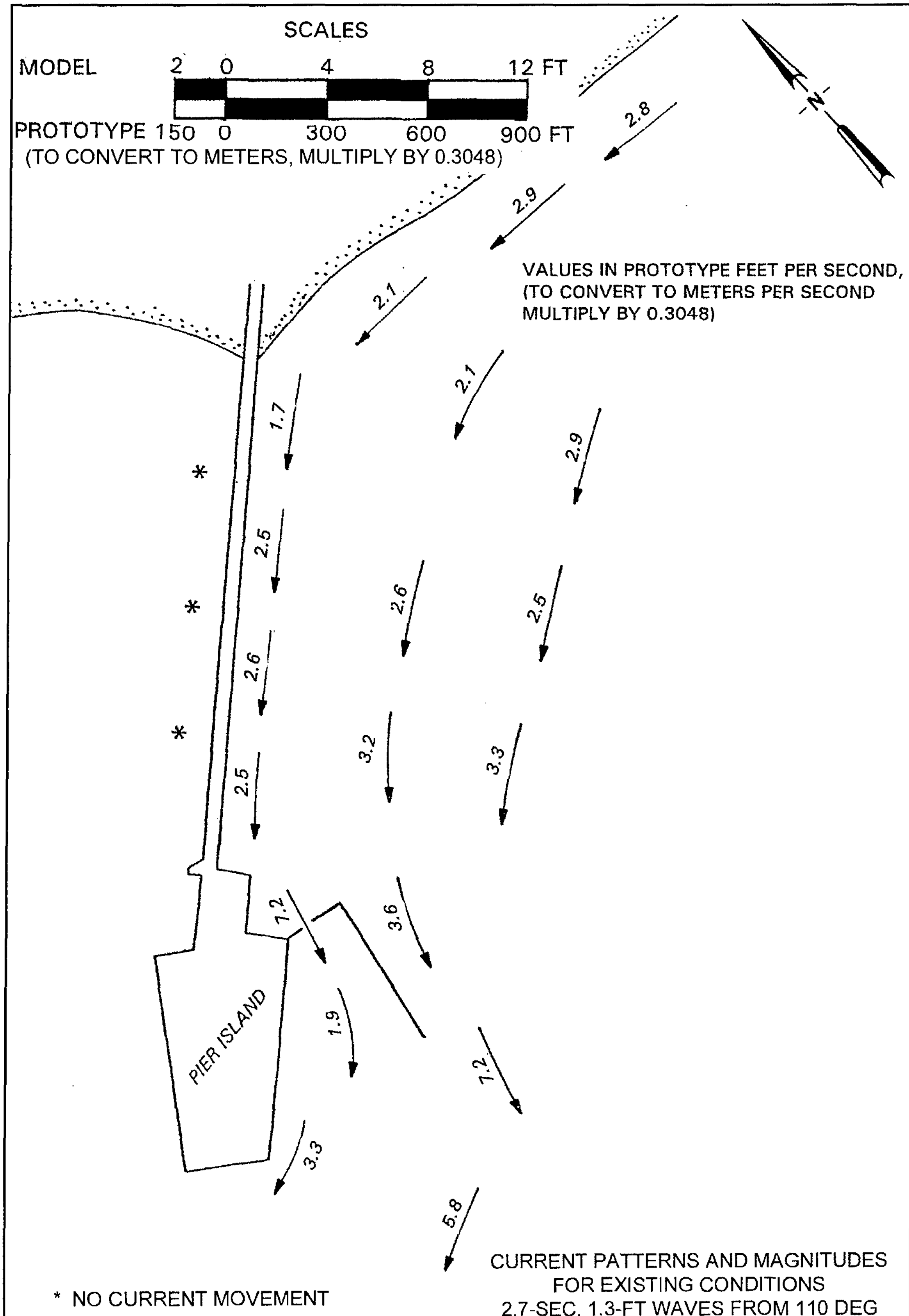
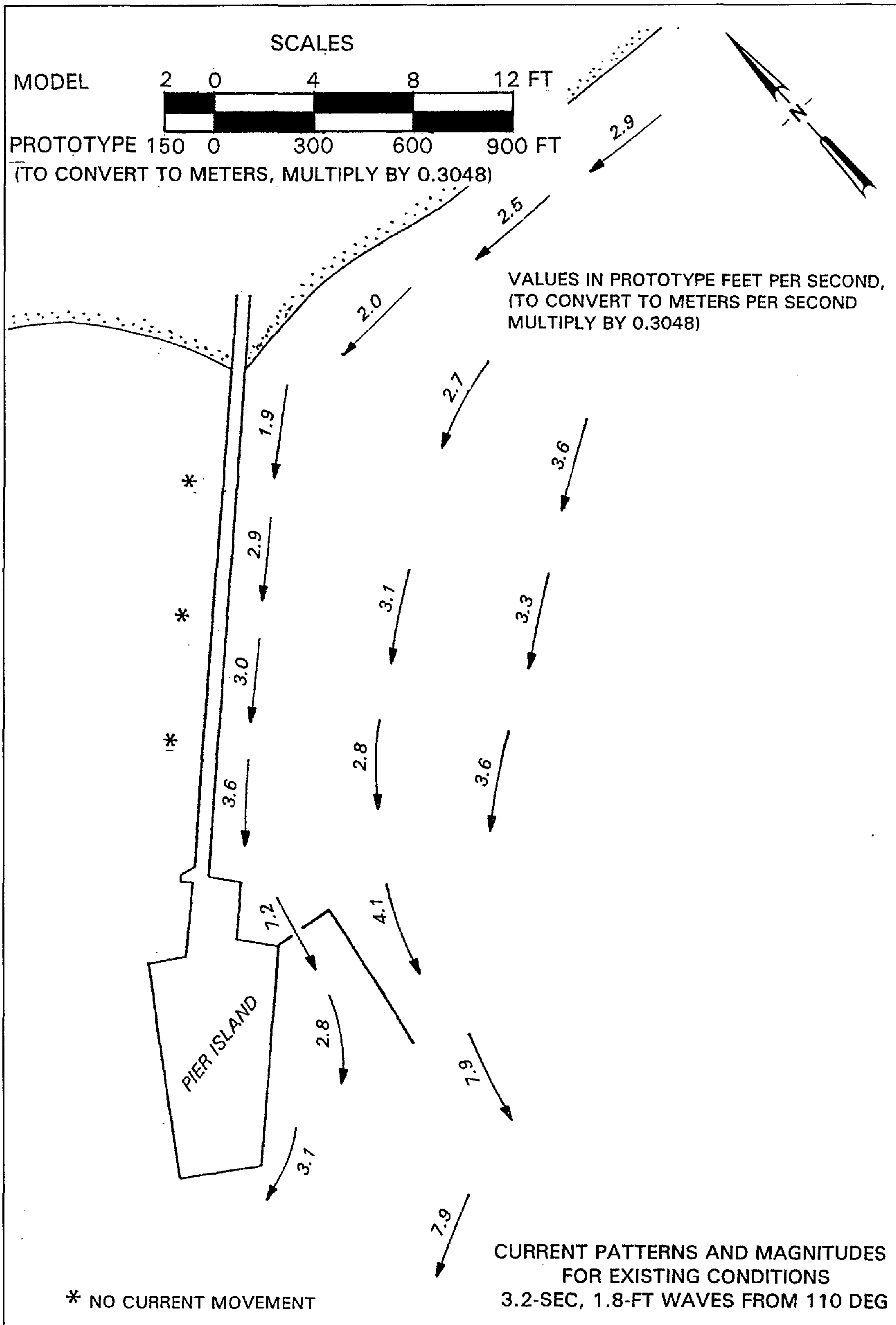

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
VALUES IN PROTOTYPE FEET PER SECOND, (TO CONVERT TO METERS PER SECOND MULTIPLY BY 0.3048)
2.8
2.9
2.1
2.1
1.7
2.9
2.5
2.6
2.5
2.6
3.2
3.3
2.5
7.2
3.6
1.9
7.2
PIER ISLAND
3.3
5.8
* NO CURRENT MOVEMENT
CURRENT PATTERNS AND MAGNITUDES FOR EXISTING CONDITIONS 2.7-SEC, 1.3-FT WAVES FROM 110 DEG

Plate 12



SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
2.9
2.5
2.0
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
1.9
2.7
3.6
*
2.9
3.1
3.3
*
3.0
*
3.6
2.8
3.6
7.2
4.1
PIER ISLAND
2.8
7.9
3.1
7.9
* NO CURRENT MOVEMENT
CURRENT PATTERNS AND MAGNITUDES
FOR EXISTING CONDITIONS
3.2-SEC, 1.8-FT WAVES FROM 110 DEG

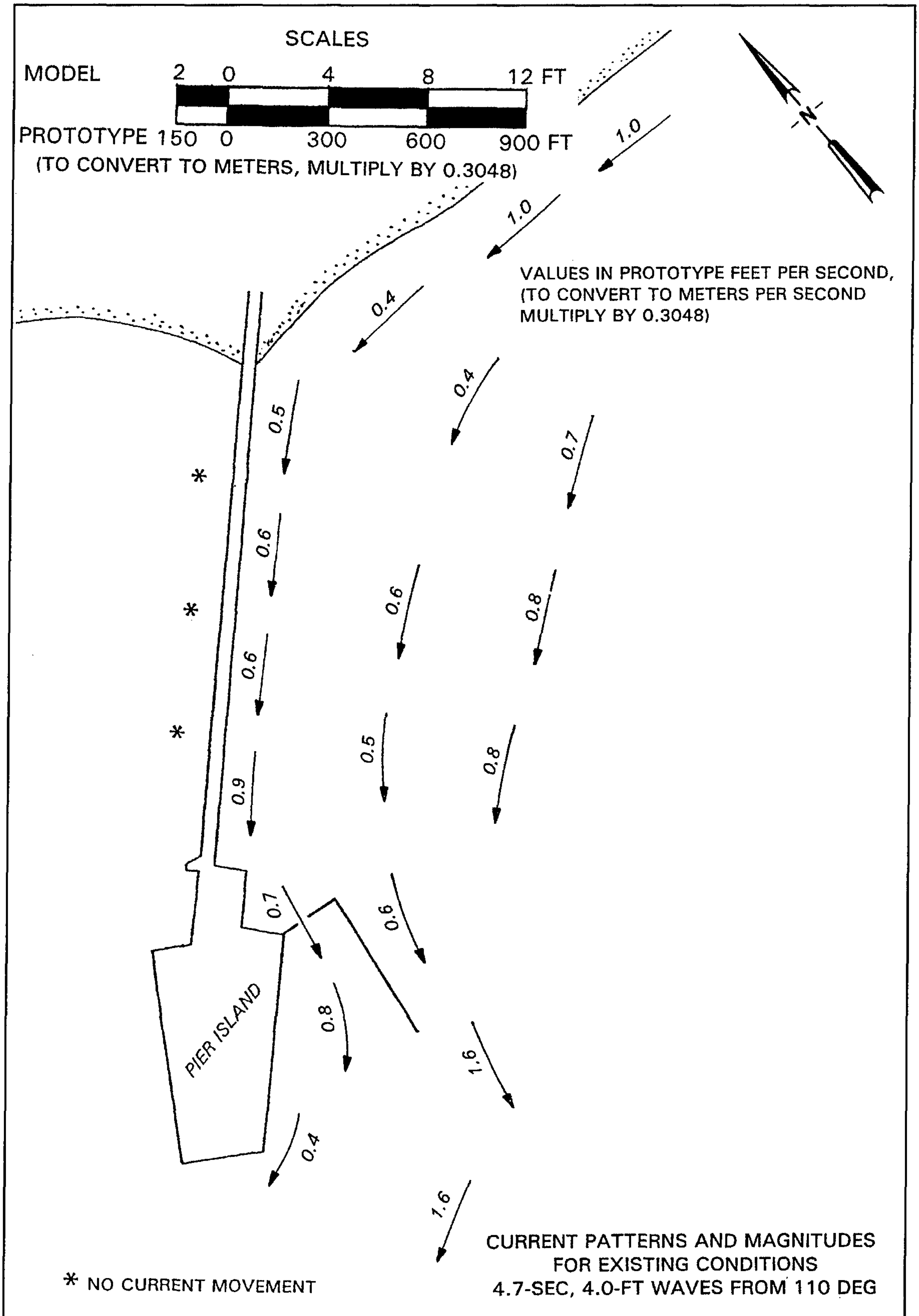
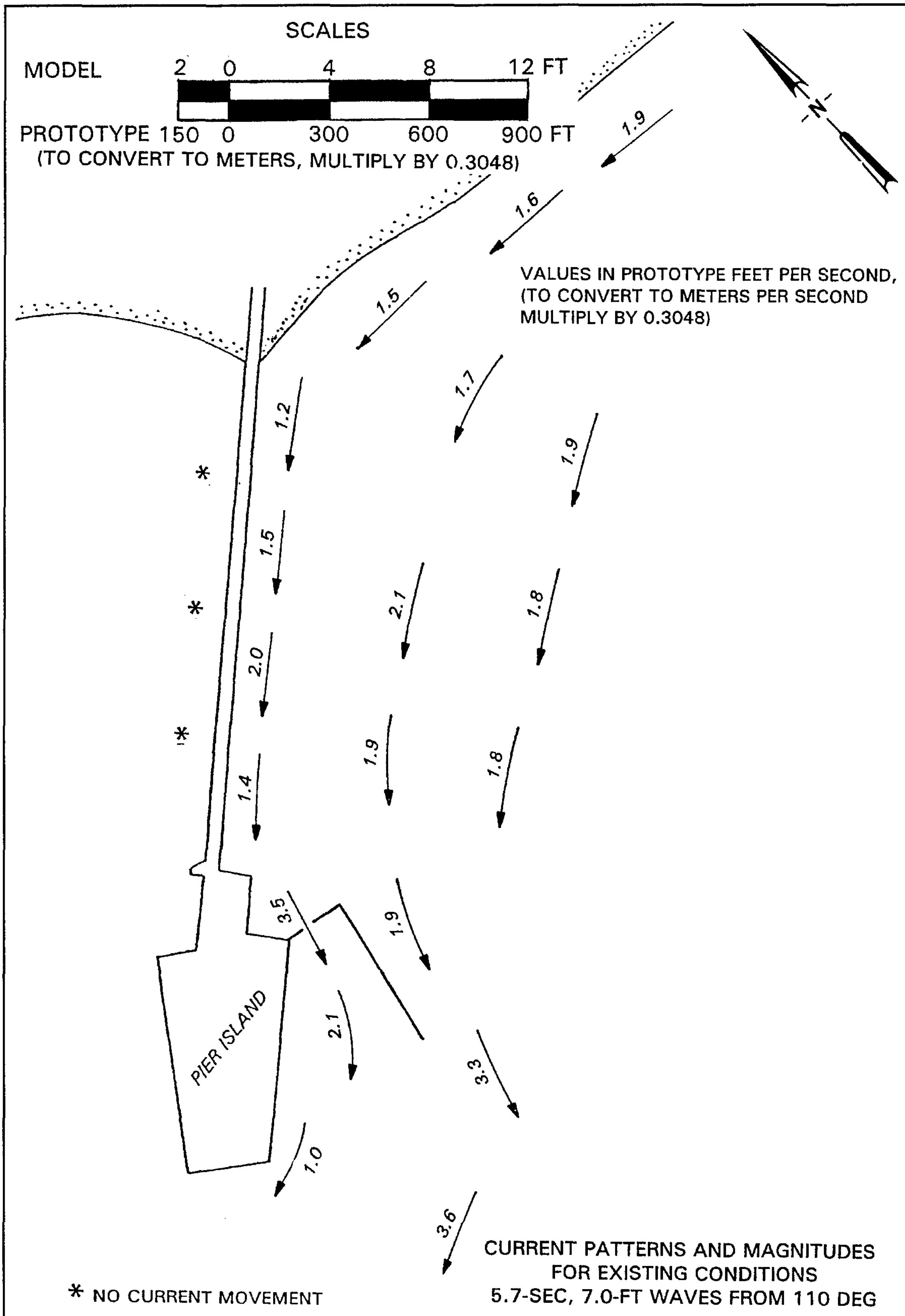
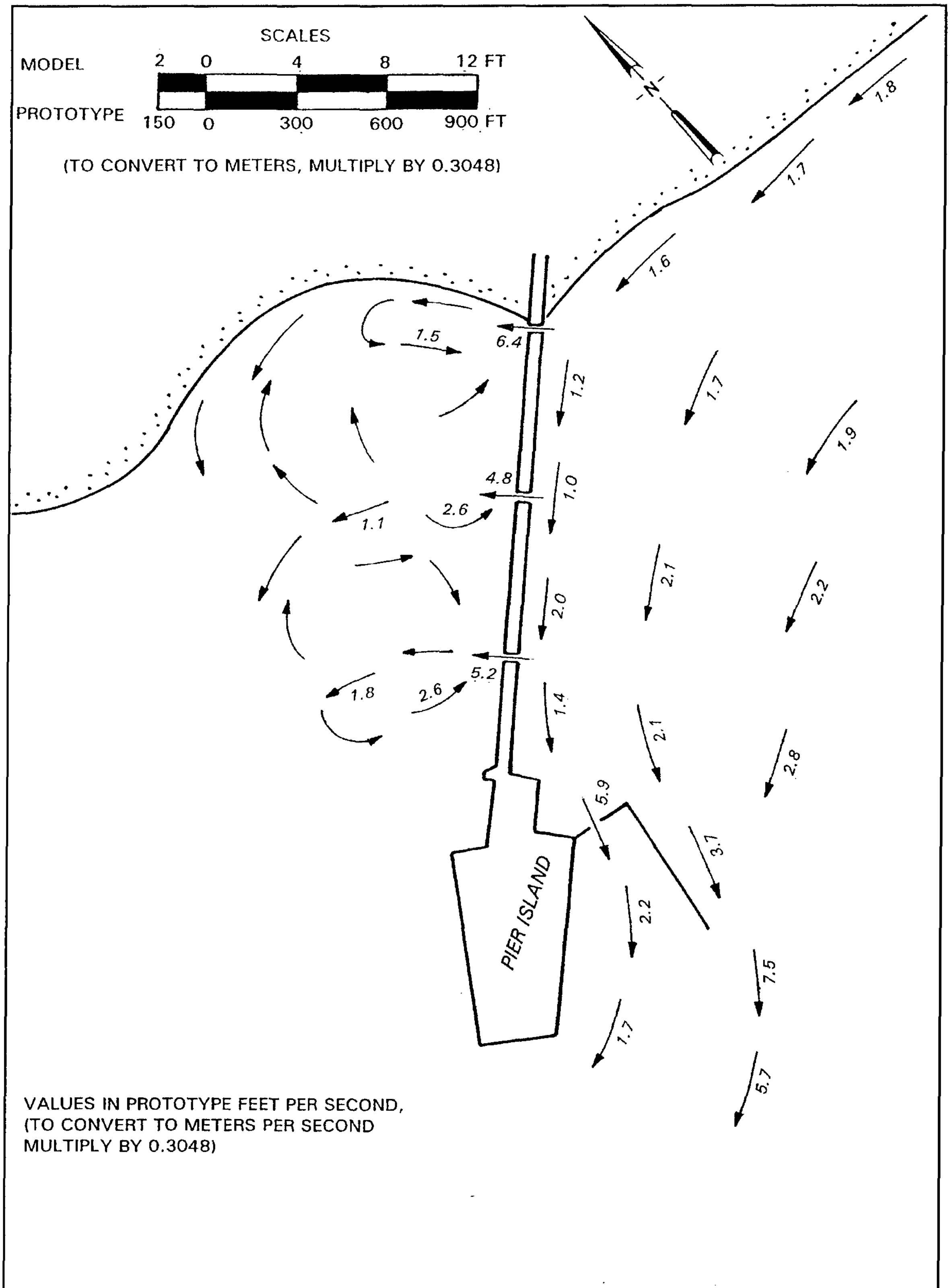
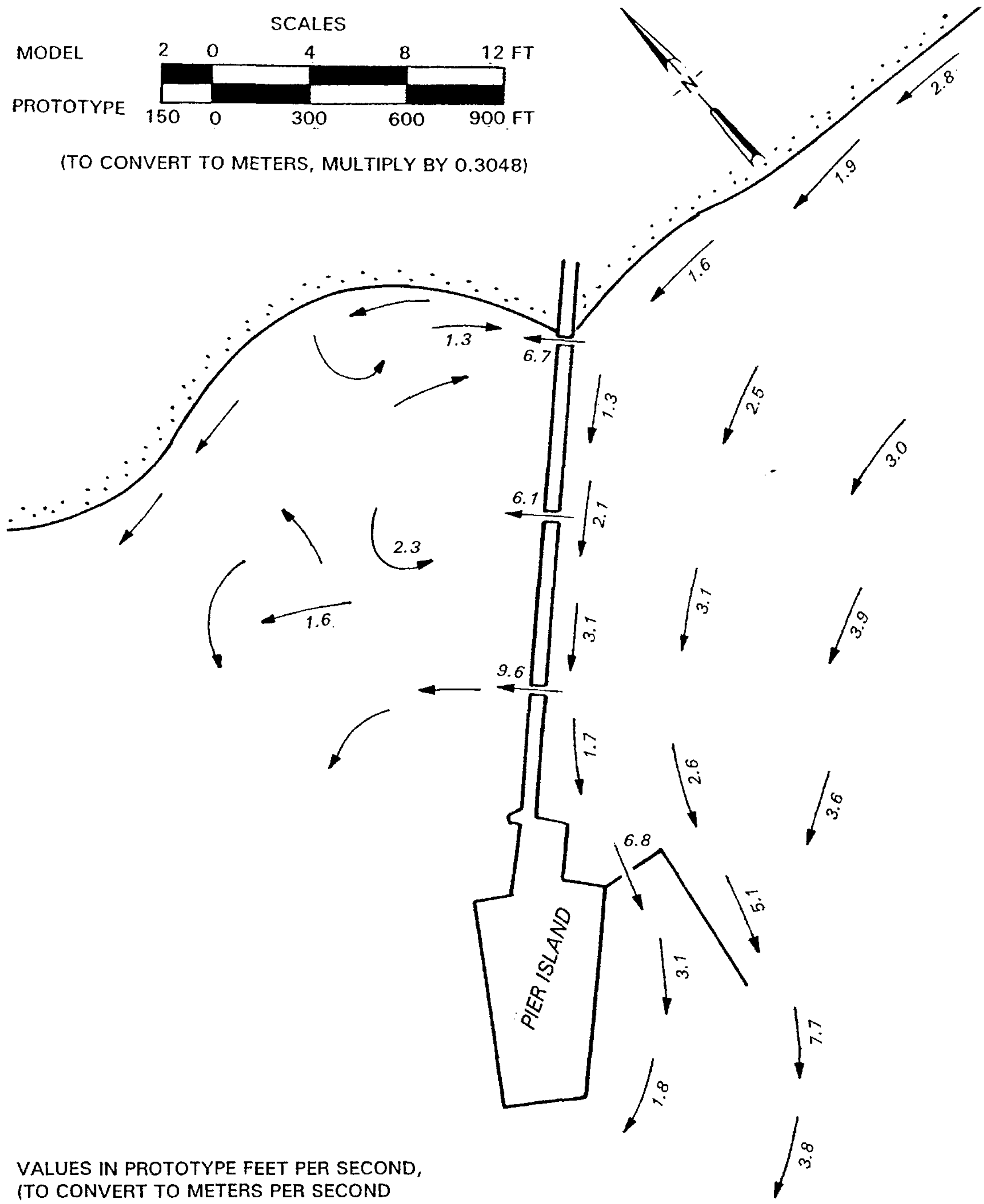

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
1.0
1.0
0.4
0.4
0.5
0.7
0.6
0.6
0.8
0.6
0.5
0.8
0.9
0.7
0.6
0.8
1.6
0.4
1.6
PIER ISLAND
* NO CURRENT MOVEMENT
CURRENT PATTERNS AND MAGNITUDES
FOR EXISTING CONDITIONS
4.7-SEC, 4.0-FT WAVES FROM 110 DEG

Plate 14


SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
1.9
1.6
1.5
1.7
1.2
1.9
1.5
2.1
1.8
2.0
1.9
1.8
1.4
3.5
1.9
PIER ISLAND
2.1
3.3
1.0
3.6
*
*
*
* NO CURRENT MOVEMENT
CURRENT PATTERNS AND MAGNITUDES
FOR EXISTING CONDITIONS
5.7-SEC, 7.0-FT WAVES FROM 110 DEG

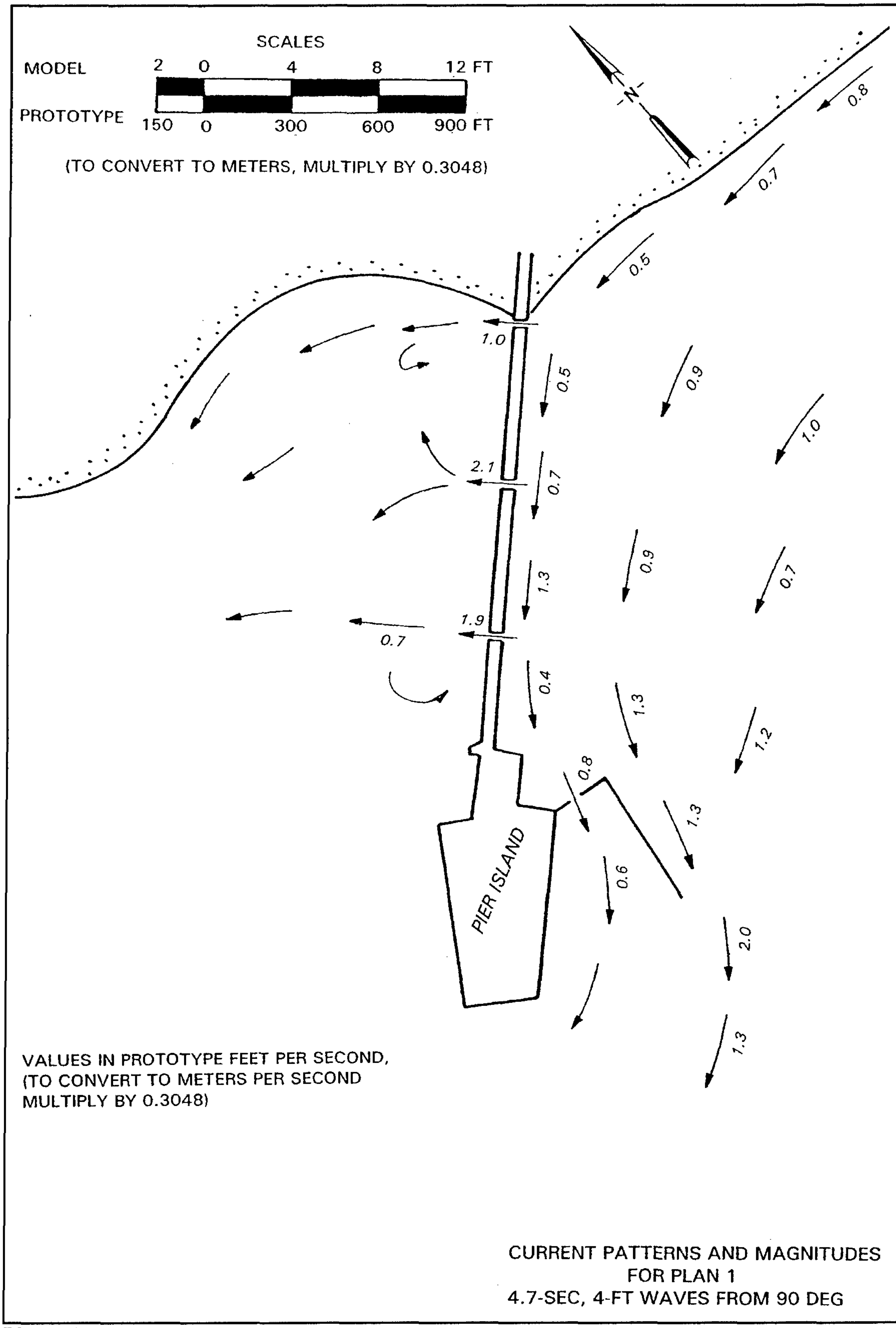


CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 1
2.7-SEC, 1.3-FT WAVES FROM 90 DEG



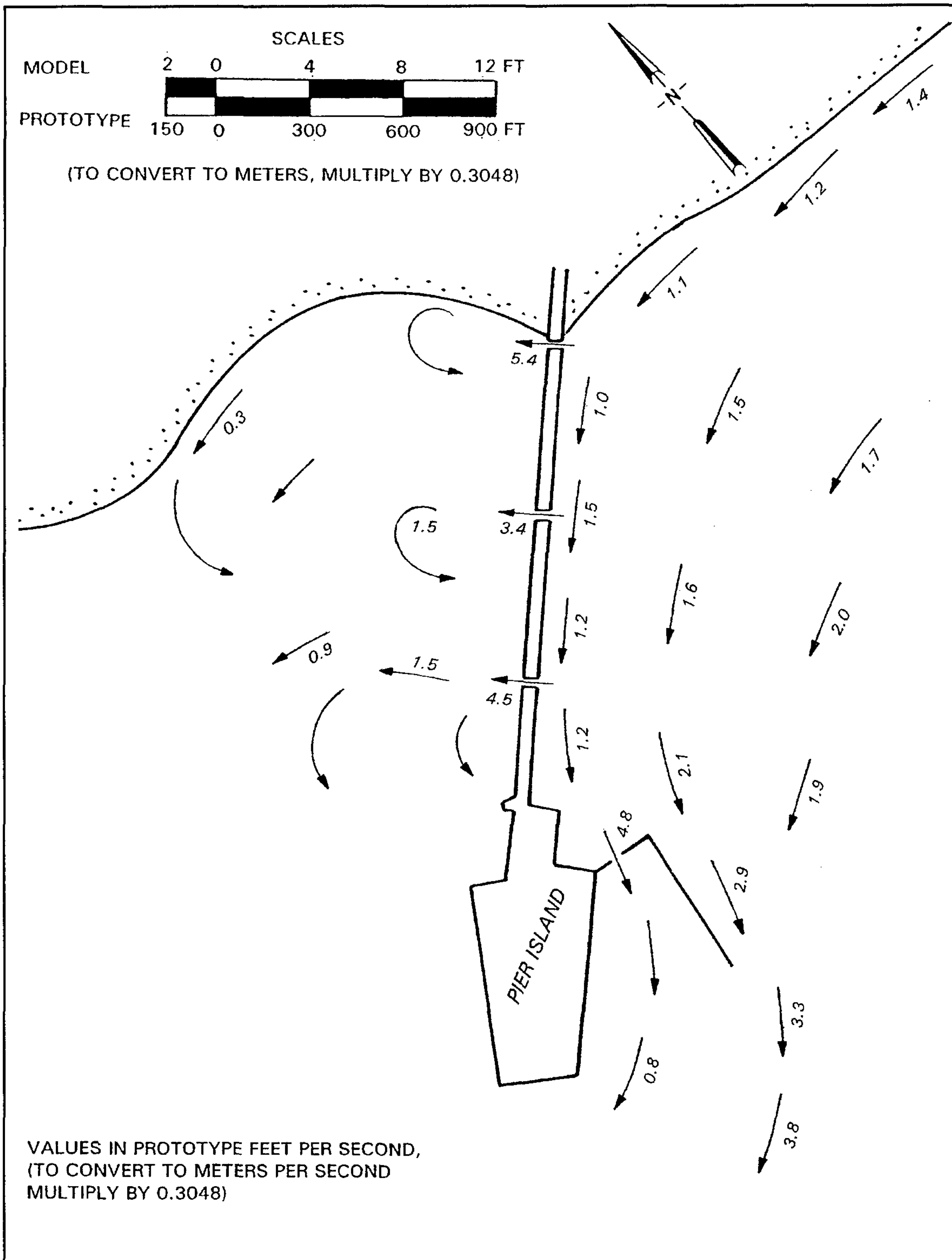
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)

CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 1
3.2-SEC, 1.8-FT WAVES FROM 90 DEG

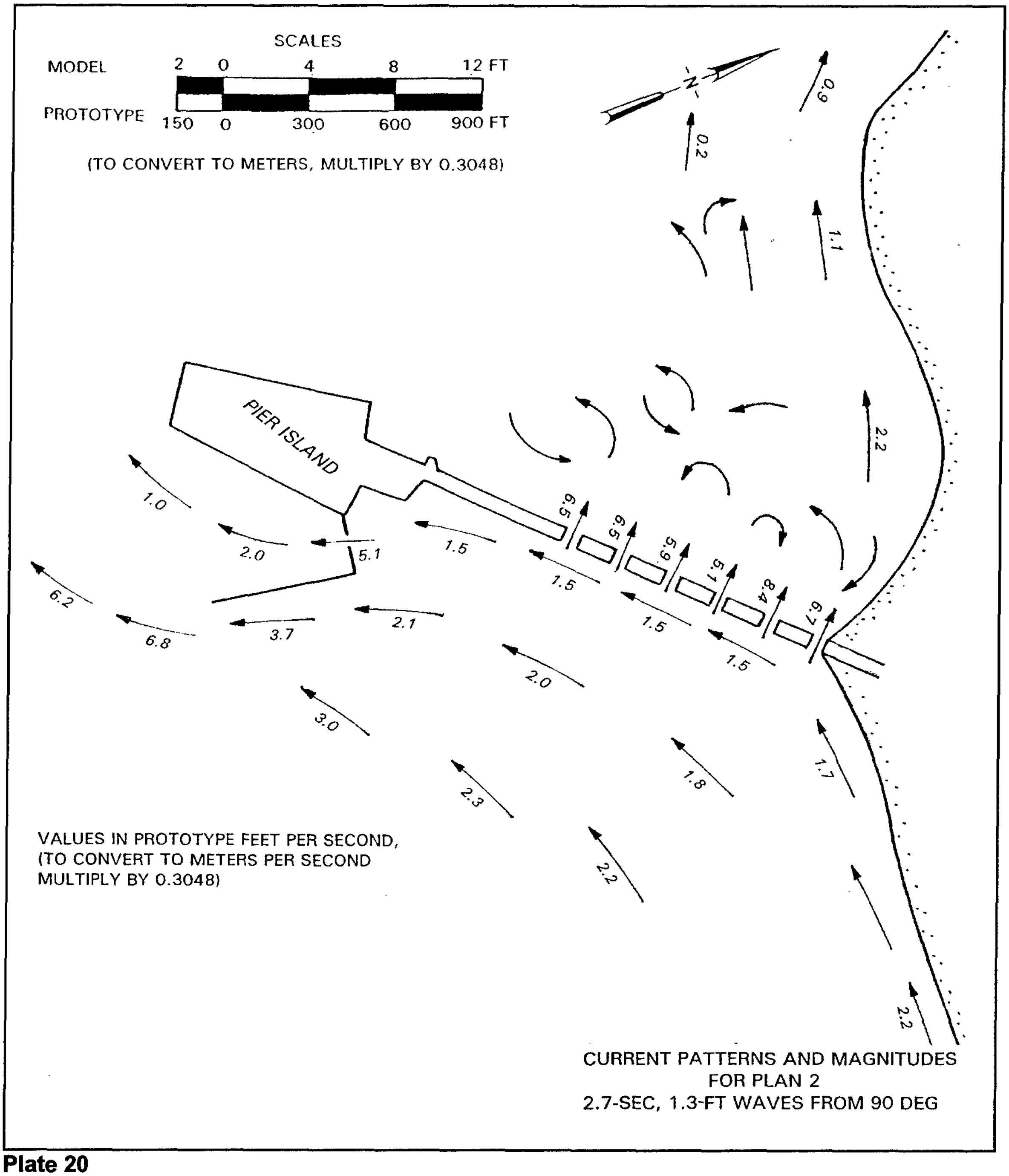


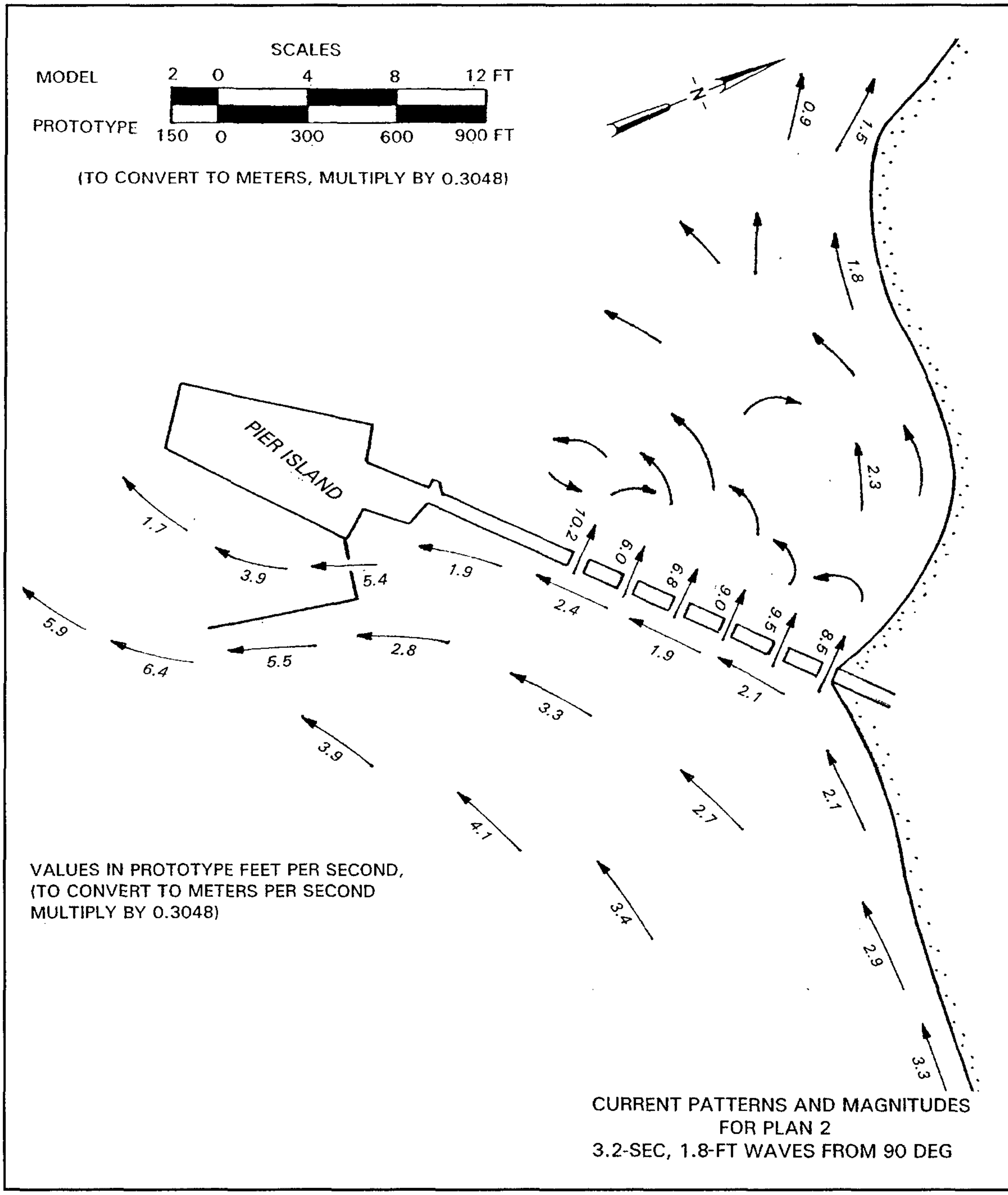
CURRENT PATTERNS AND MAGNITUDES FOR PLAN 1
4.7-SEC, 4-FT WAVES FROM 90 DEG

Plate 18



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 1
5.7-SEC, 7-FT WAVES FROM 90 DEG


SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
0.9
0.2
1.1
2.2
1.0
2.0
5.1
1.5
6.5
6.5
5.9
5.1
8.4
6.7
1.5
1.5
1.5
6.2
6.8
3.7
2.1
2.0
3.0
1.8
1.7
2.3
2.2
2.2
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 2
2.7-SEC, 1.3-FT WAVES FROM 90 DEG



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 2
3.2-SEC, 1.8-FT WAVES FROM 90 DEG

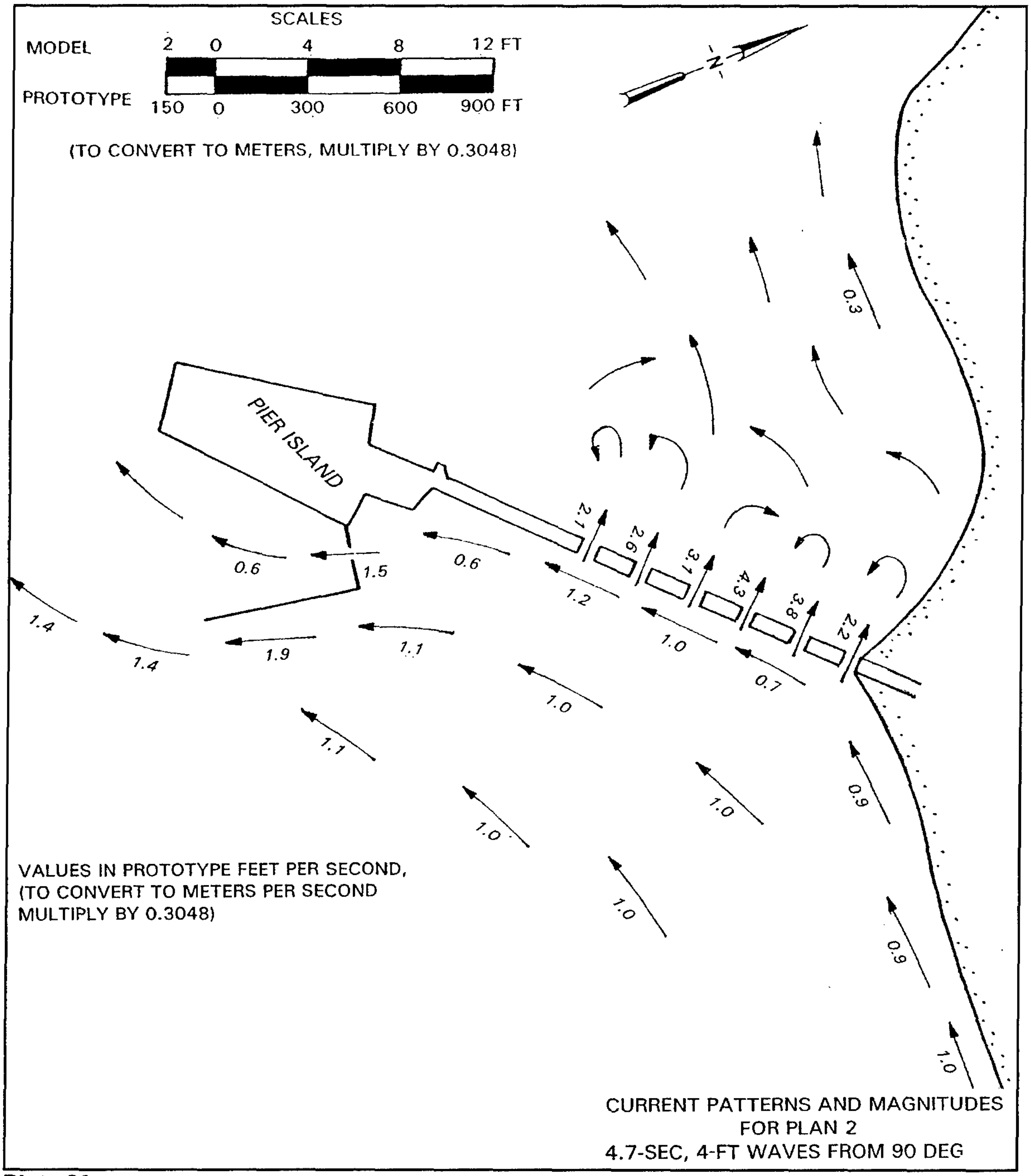
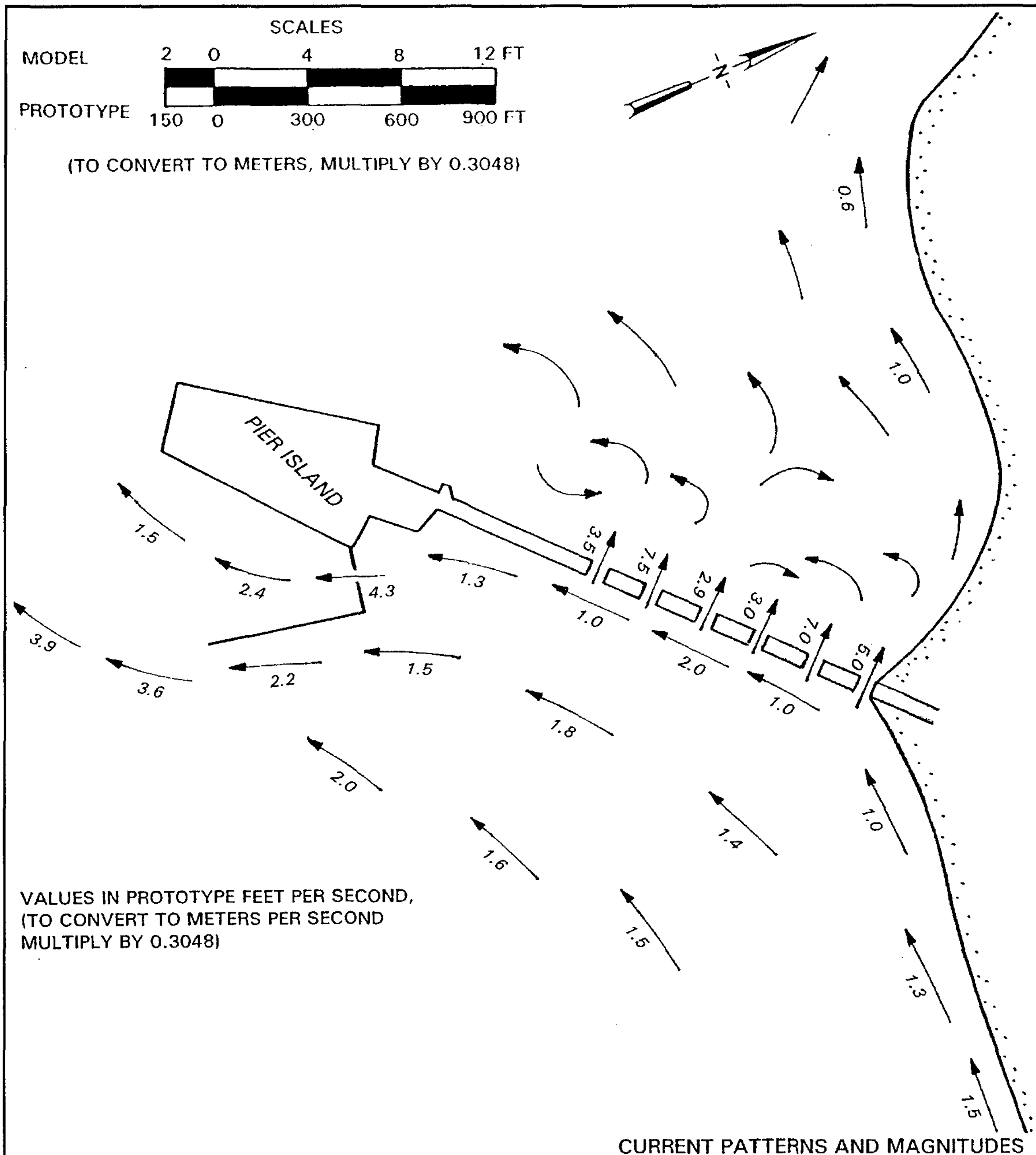
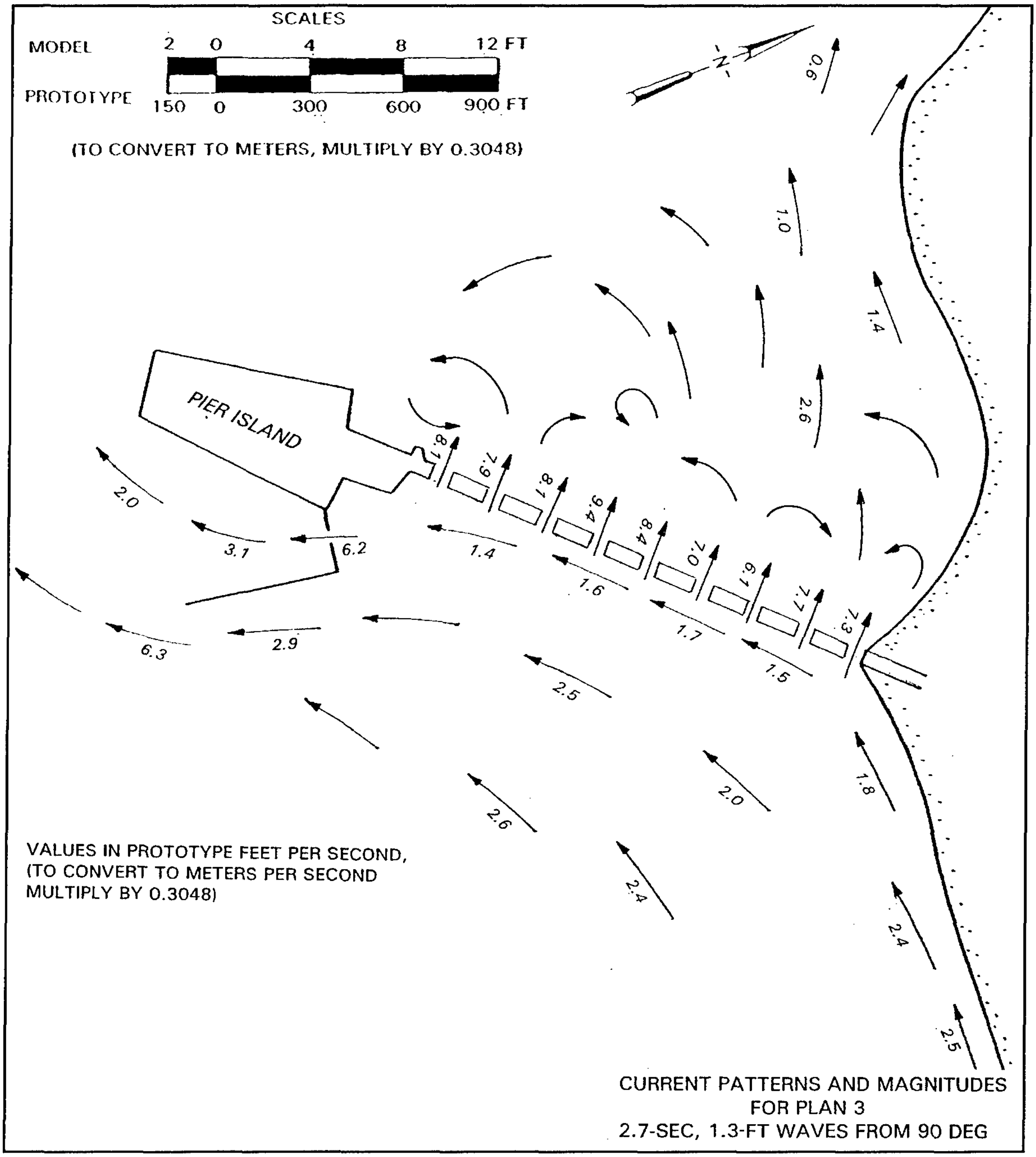

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
0.3
2.1
2.6
3.1
4.3
3.8
2.2
0.6
1.5
0.6
1.2
1.0
0.7
1.4
1.4
1.9
1.1
1.0
1.1
1.0
1.0
0.9
1.0
0.9
1.0
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 2
4.7-SEC, 4-FT WAVES FROM 90 DEG

Plate 22

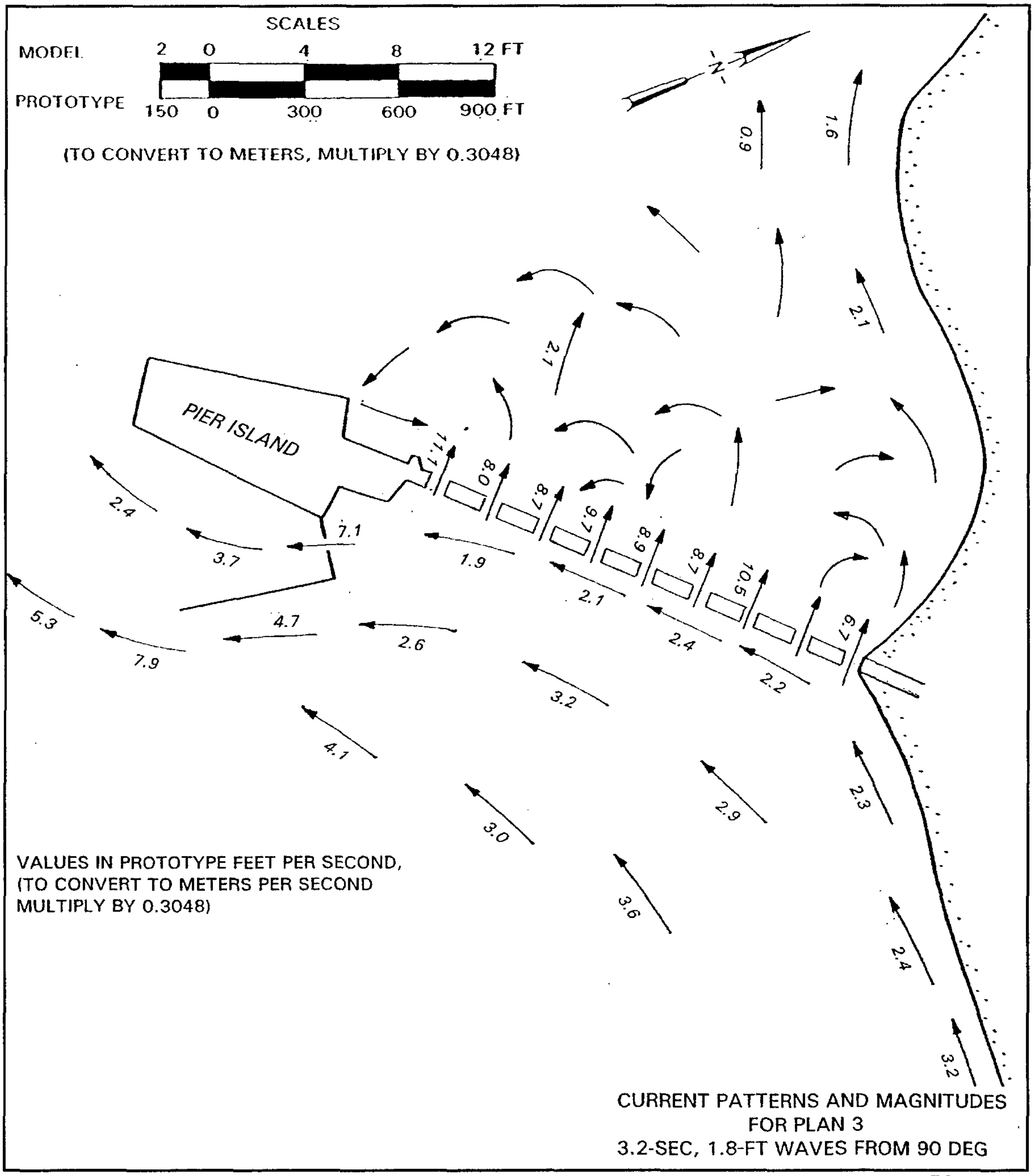


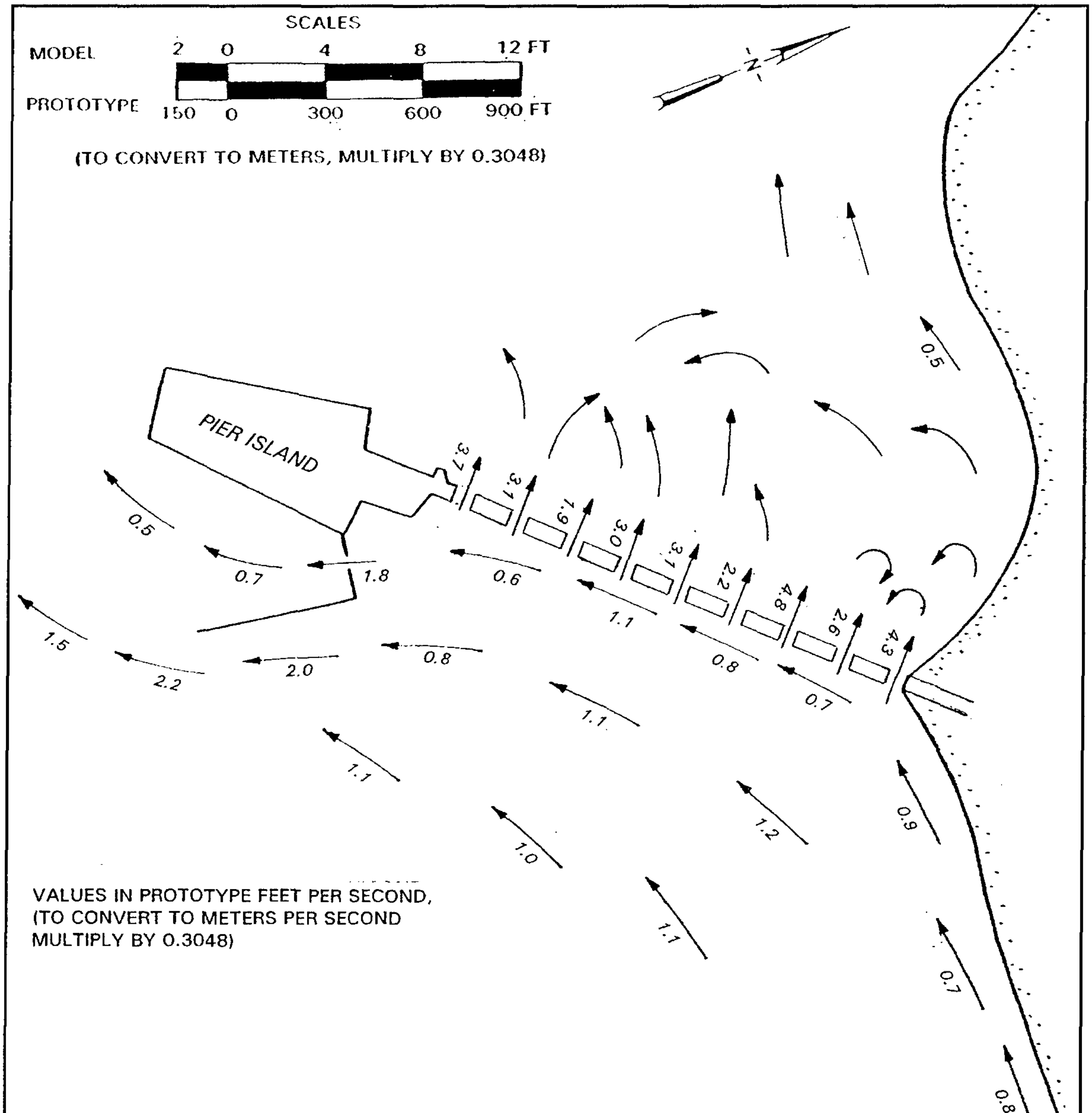
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 2
5.7-SEC, 7-FT WAVES FROM 90 DEG



SCALES
MODEL
2 0 4 8 12 FT
PROTOTYPE
150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
0.6
1.0
1.4
2.6
8.1
7.9
8.1
9.4
8.4
7.0
6.1
7.7
7.3
2.0
3.1
6.2
1.4
1.6
1.7
1.5
6.3
2.9
2.5
2.6
2.0
1.8
2.4
2.4
2.5
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 3
2.7-SEC, 1.3-FT WAVES FROM 90 DEG

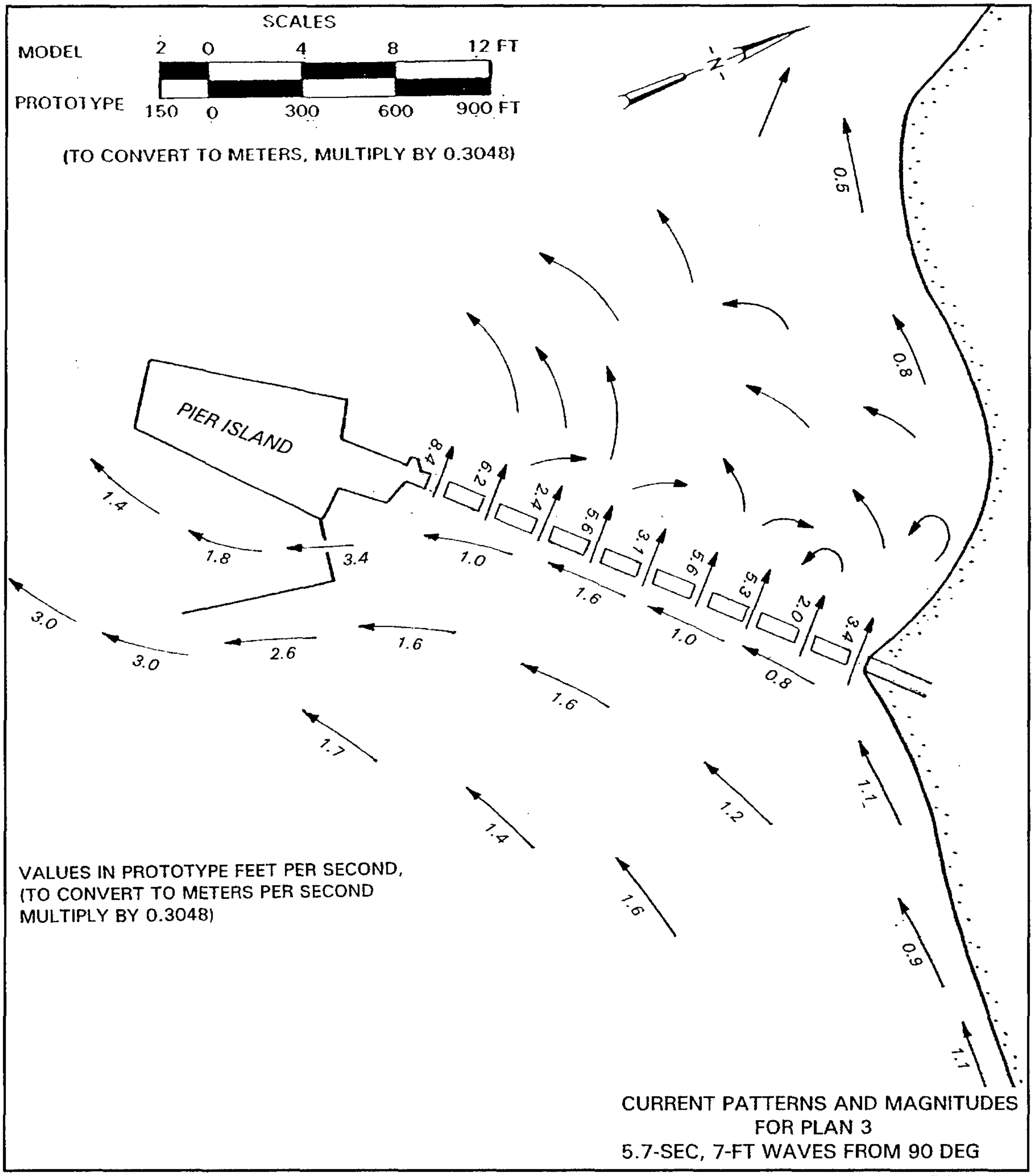
Plate 24

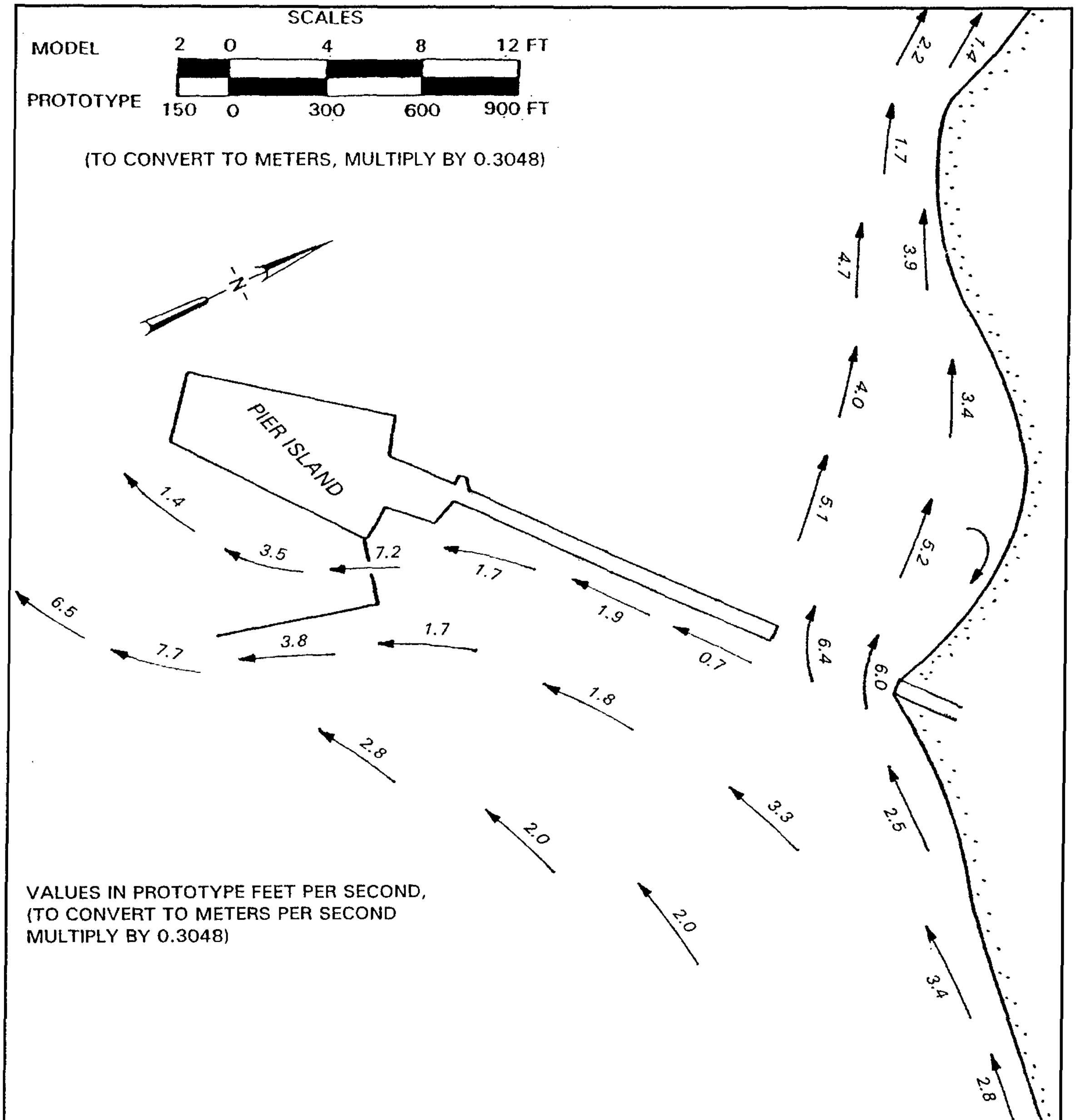

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
VALUES IN PROTOTYPE FEET PER SECOND, (TO CONVERT TO METERS PER SECOND MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 3
3.2-SEC, 1.8-FT WAVES FROM 90 DEG



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 3
4.7-SEC, 4-FT WAVES FROM 90 DEG

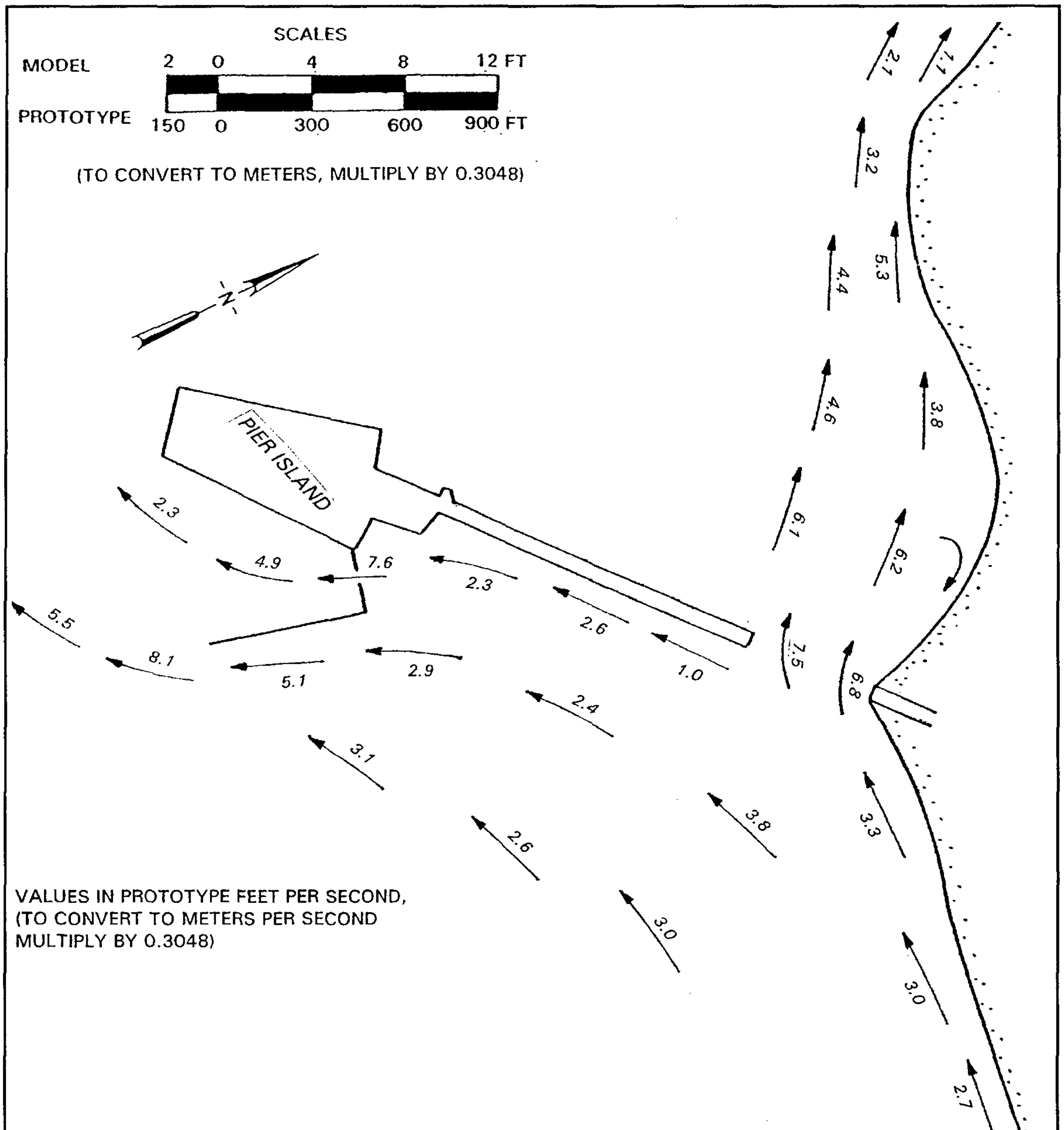
Plate 26


SCALES
MODEL
2 0 4 8 12 FT
PROTOTYPE
150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
0.5
0.8
8.4
6.2
2.4
5.6
3.1
5.6
5.3
2.0
3.4
1.4
1.8
3.4
1.0
1.6
1.0
0.8
3.0
3.0
2.6
1.6
1.6
1.7
1.4
1.2
1.1
1.6
0.9
1.1
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 3
5.7-SEC, 7-FT WAVES FROM 90 DEG



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 4
2.7-SEC, 1.3-FT WAVES FROM 90 DEG

Plate 28



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 4
3.2-SEC, 1.8-FT WAVES FROM 90 DEG

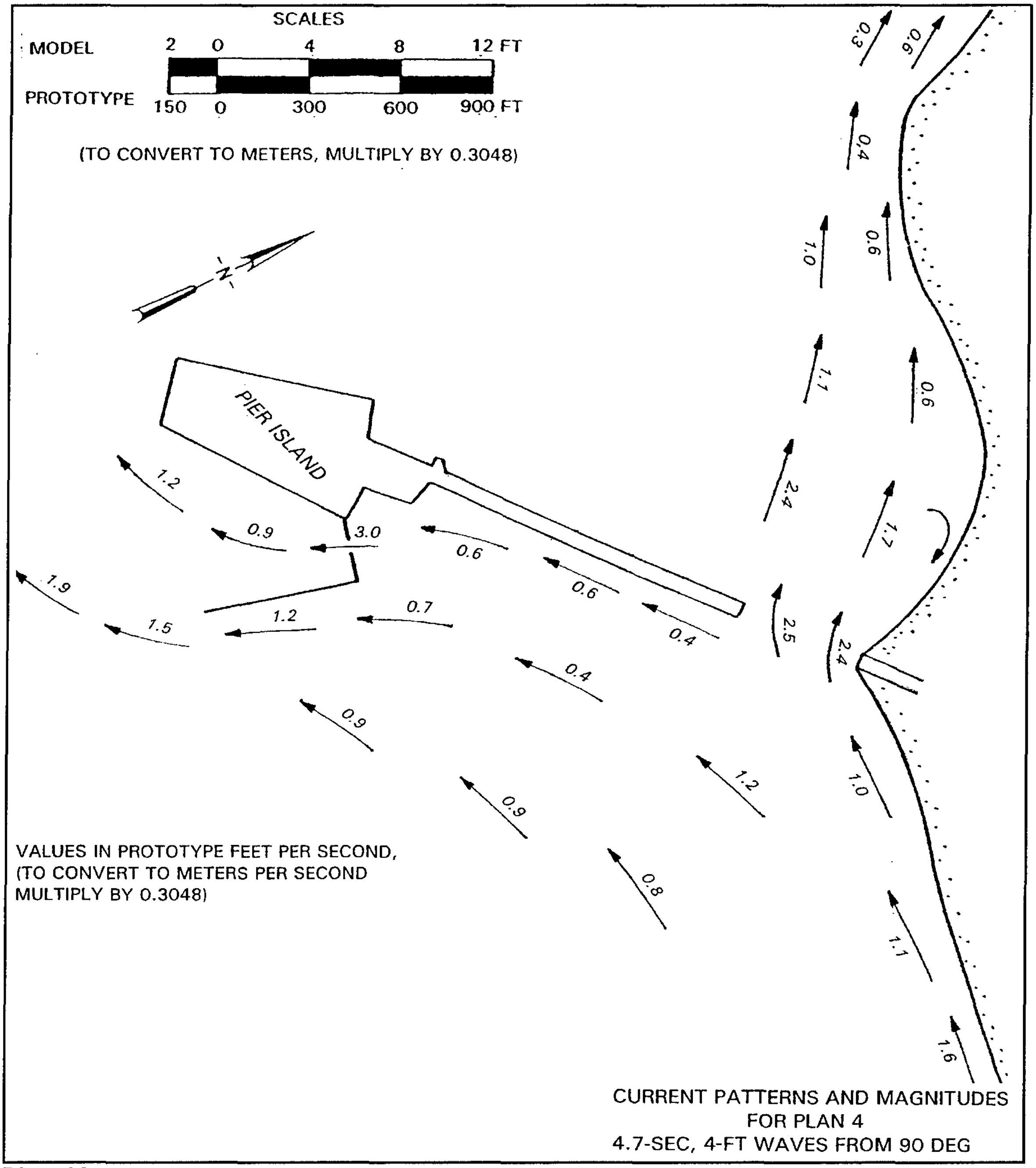

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
VALUES IN PROTOTYPE FEET PER SECOND, (TO CONVERT TO METERS PER SECOND MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES FOR PLAN 4
4.7-SEC, 4-FT WAVES FROM 90 DEG

Plate 30

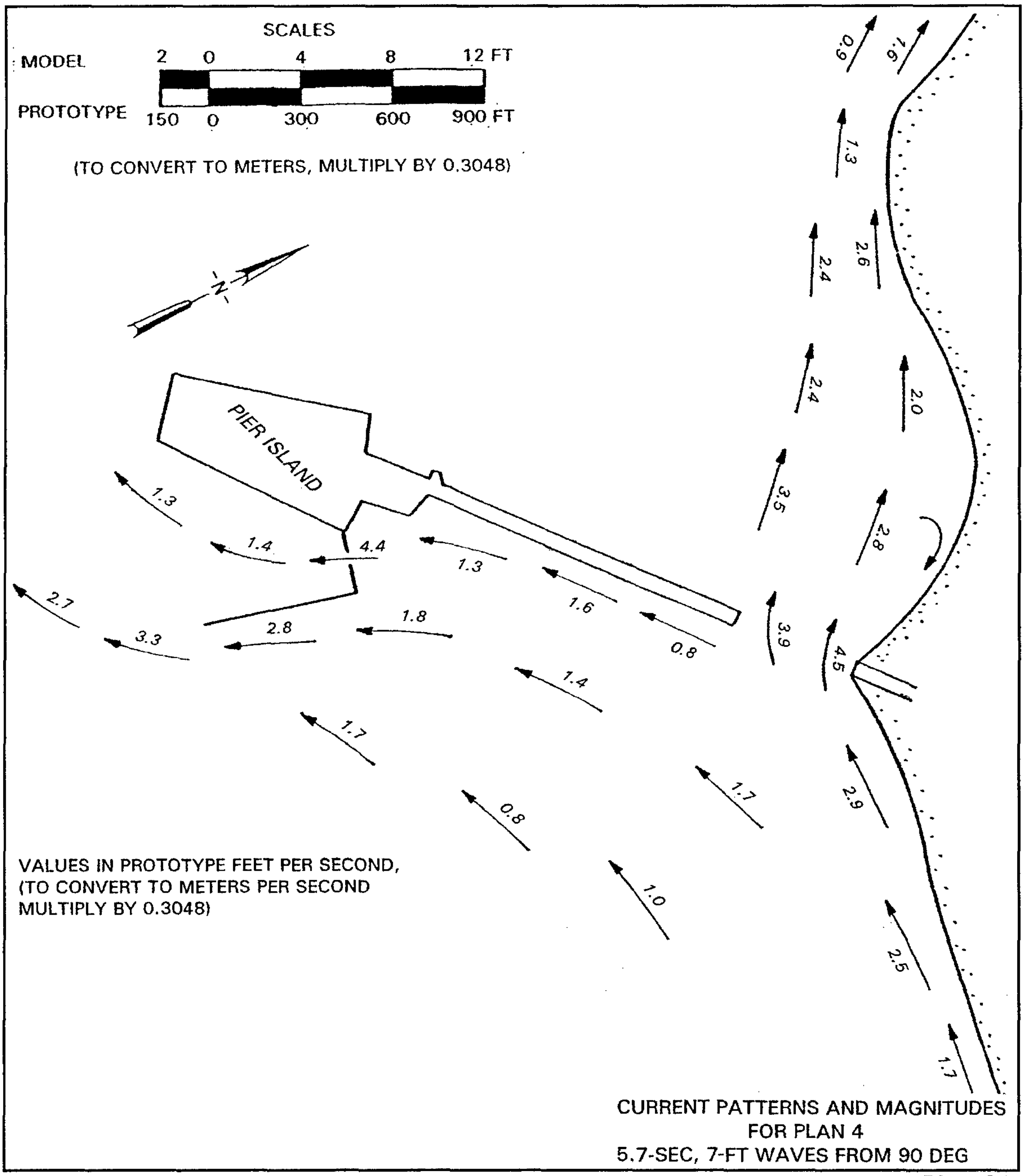

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 4
5.7-SEC, 7-FT WAVES FROM 90 DEG

Plate 31

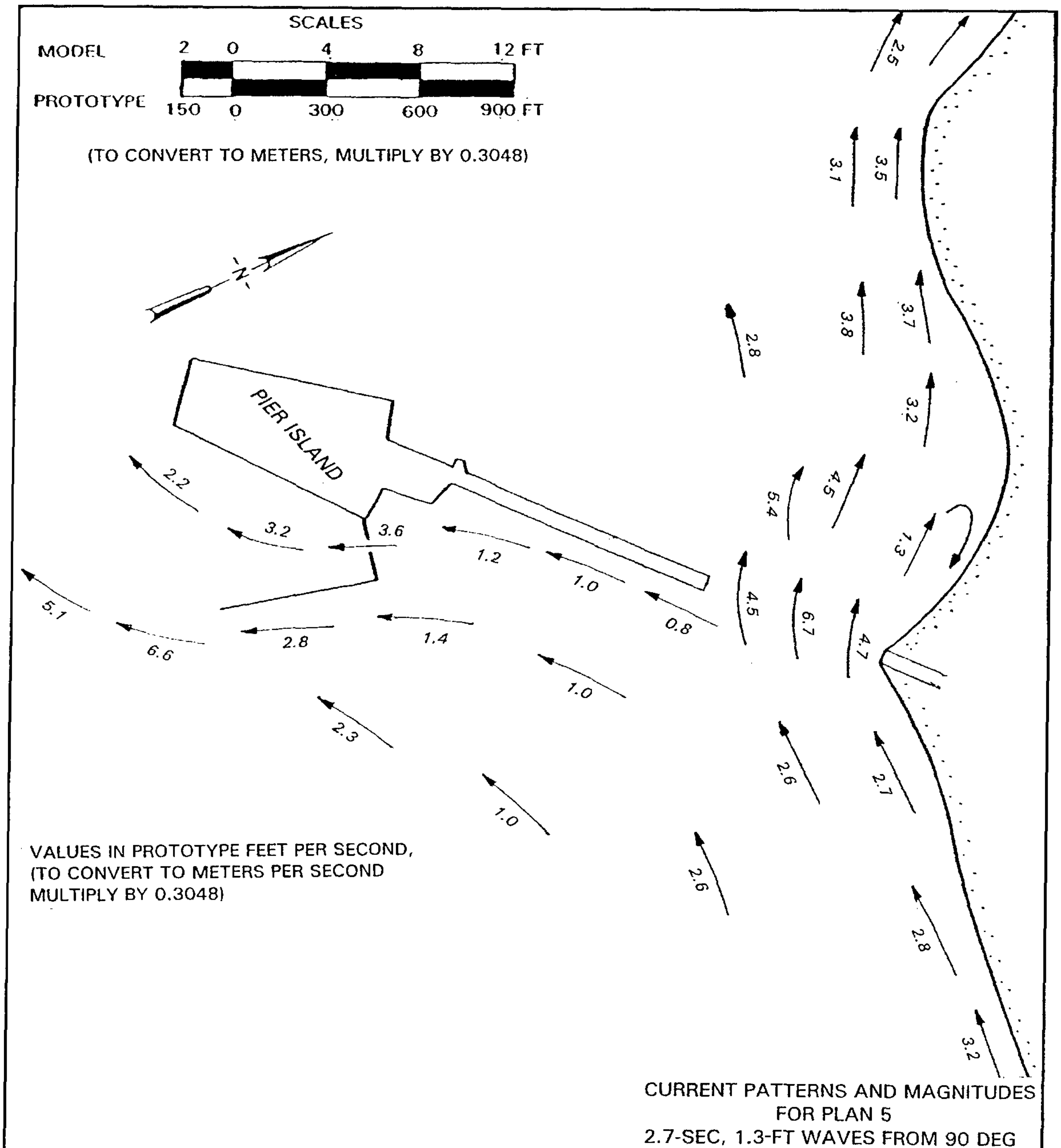
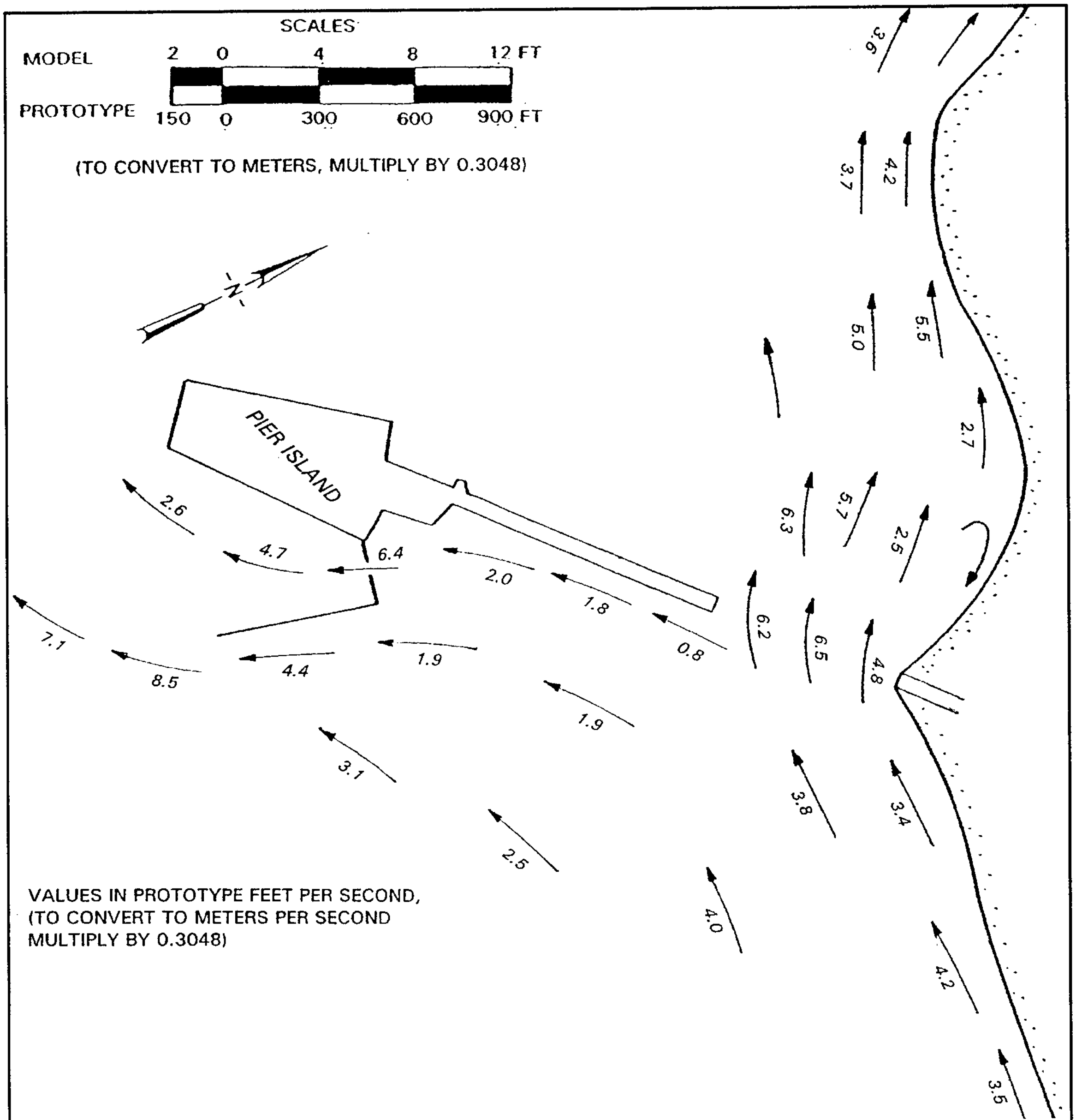

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
2.5
3.1
3.5
3.8
3.7
2.8
3.2
5.4
4.5
1.3
2.2
3.2
3.6
1.2
1.0
4.5
6.7
4.7
5.1
6.6
2.8
1.4
0.8
1.0
2.3
2.6
2.7
1.0
2.6
2.8
3.2
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 5
2.7-SEC, 1.3-FT WAVES FROM 90 DEG

Plate 32



CURRENT PATTERNS AND MAGNITUDES FOR PLAN 5
3.2-SEC, 1.8-FT WAVES FROM 90 DEG

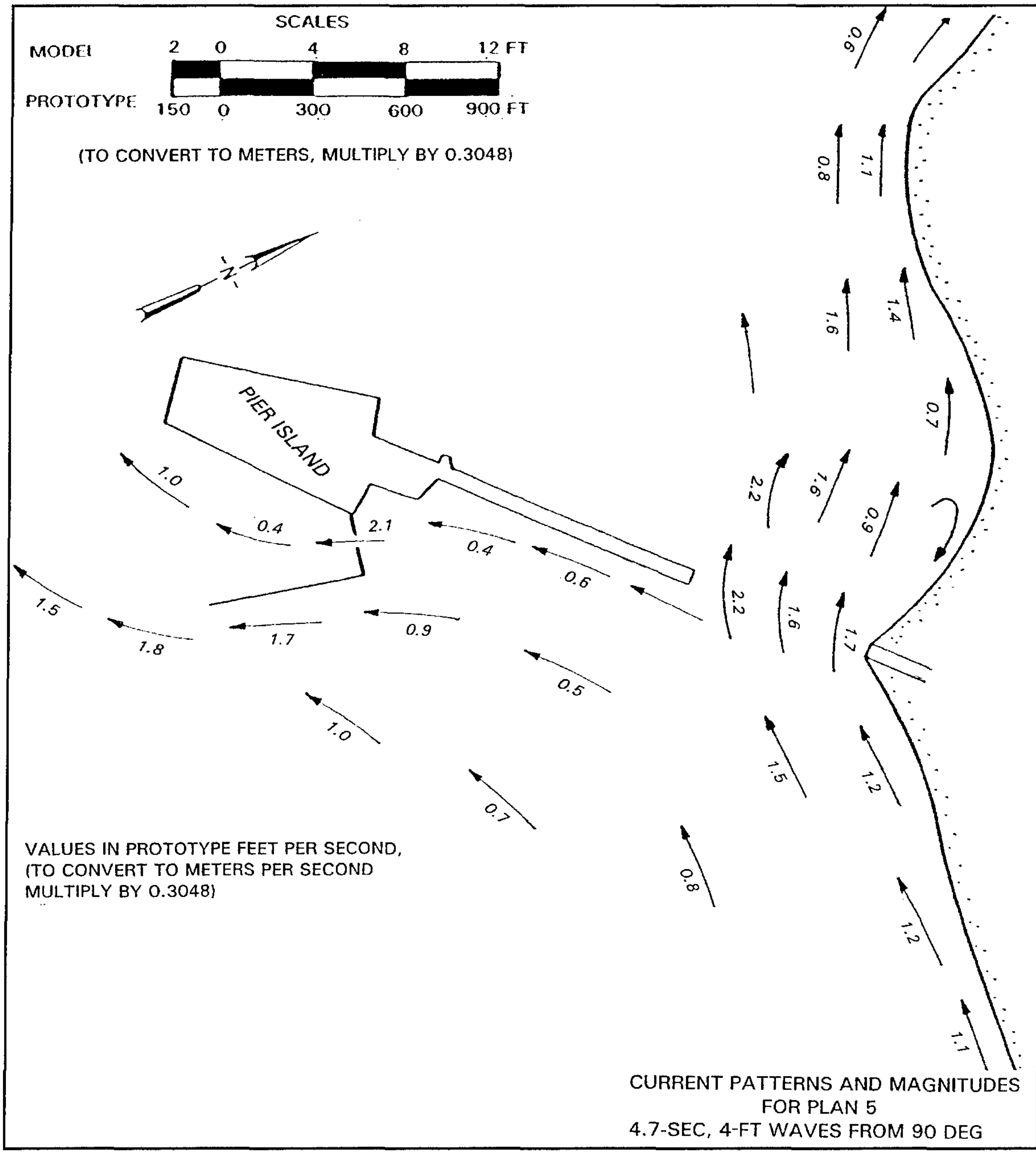
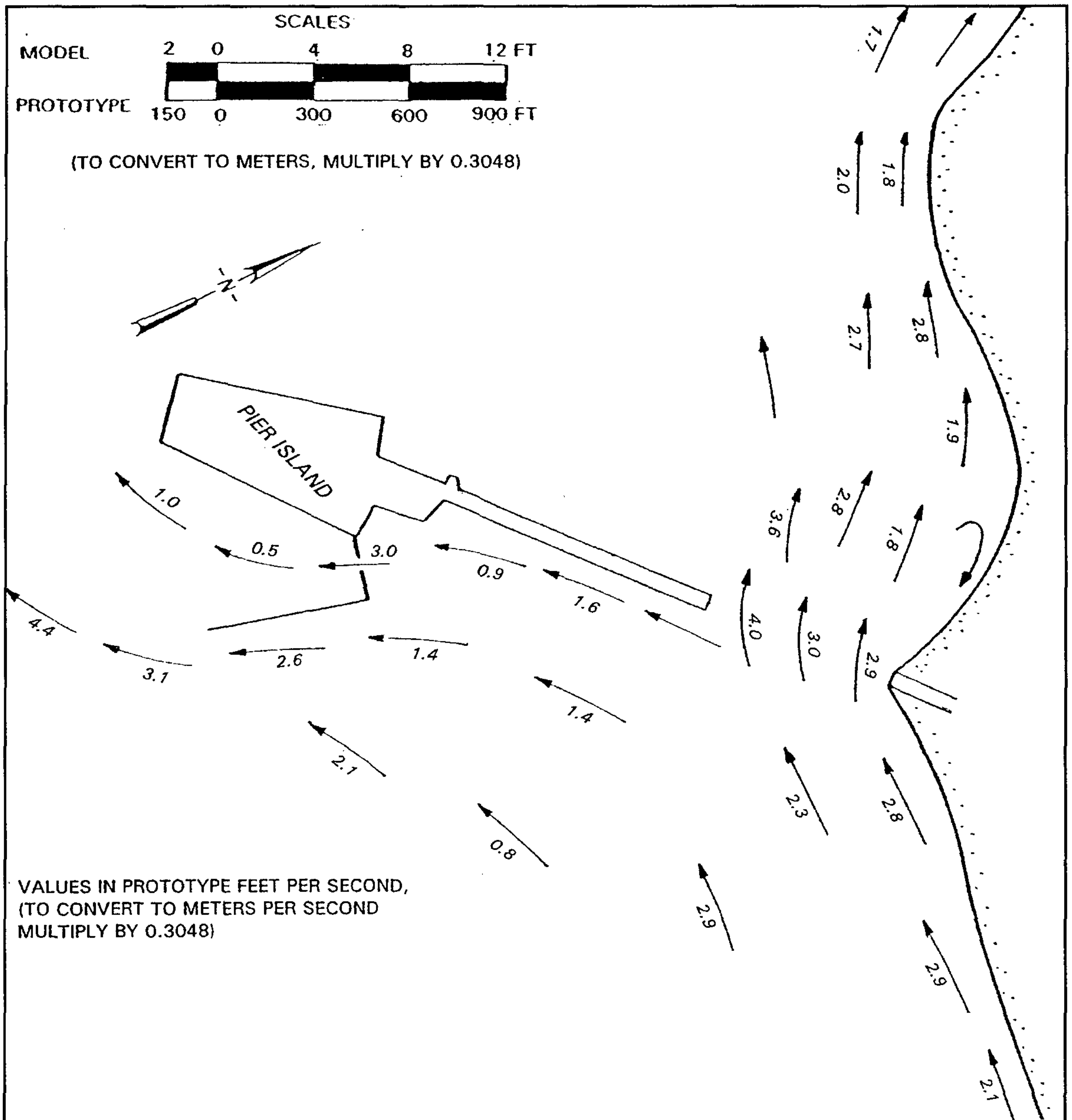
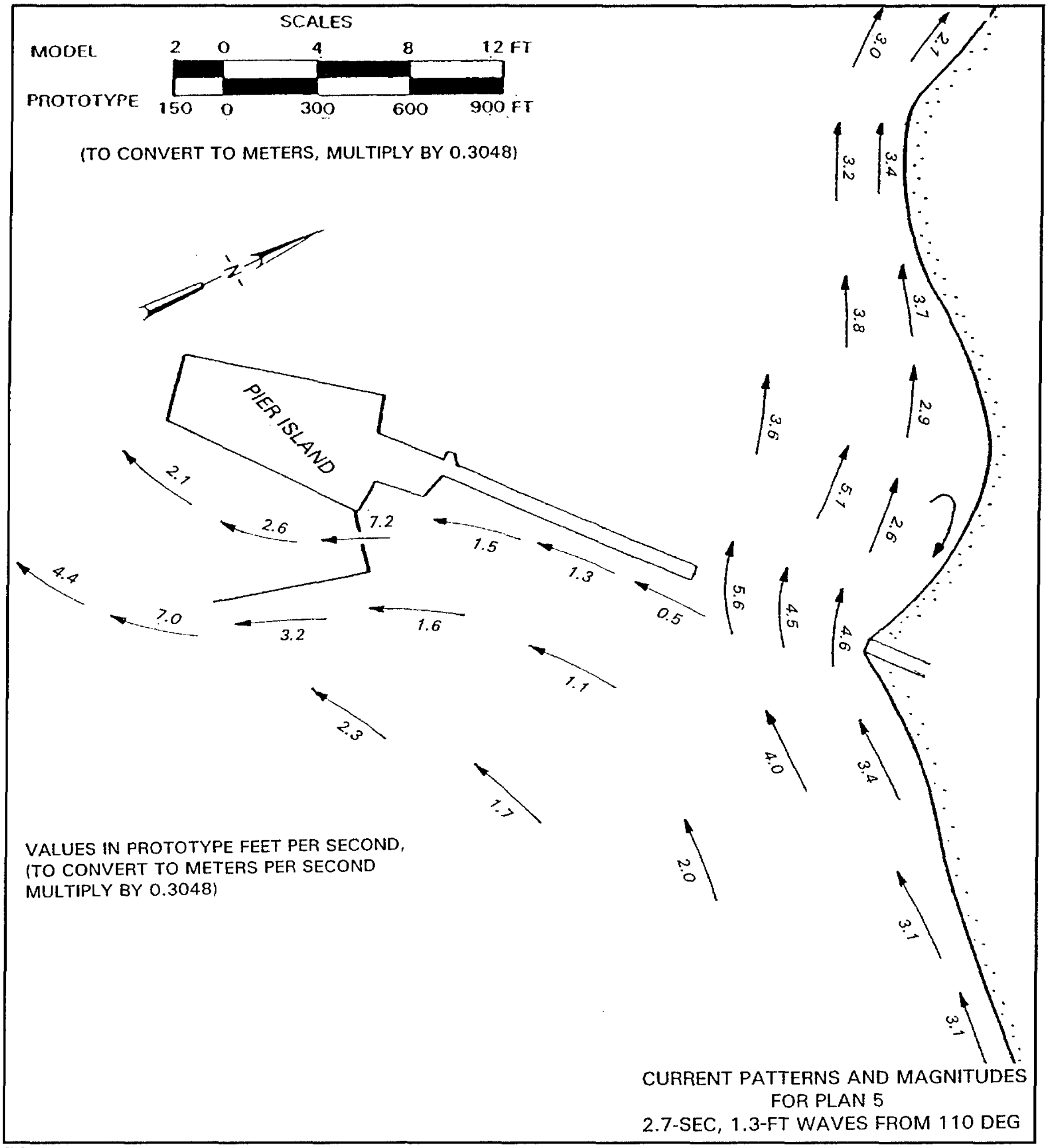

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
VALUES IN PROTOTYPE FEET PER SECOND, (TO CONVERT TO METERS PER SECOND MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES FOR PLAN 5
4.7-SEC, 4-FT WAVES FROM 90 DEG

Plate 34



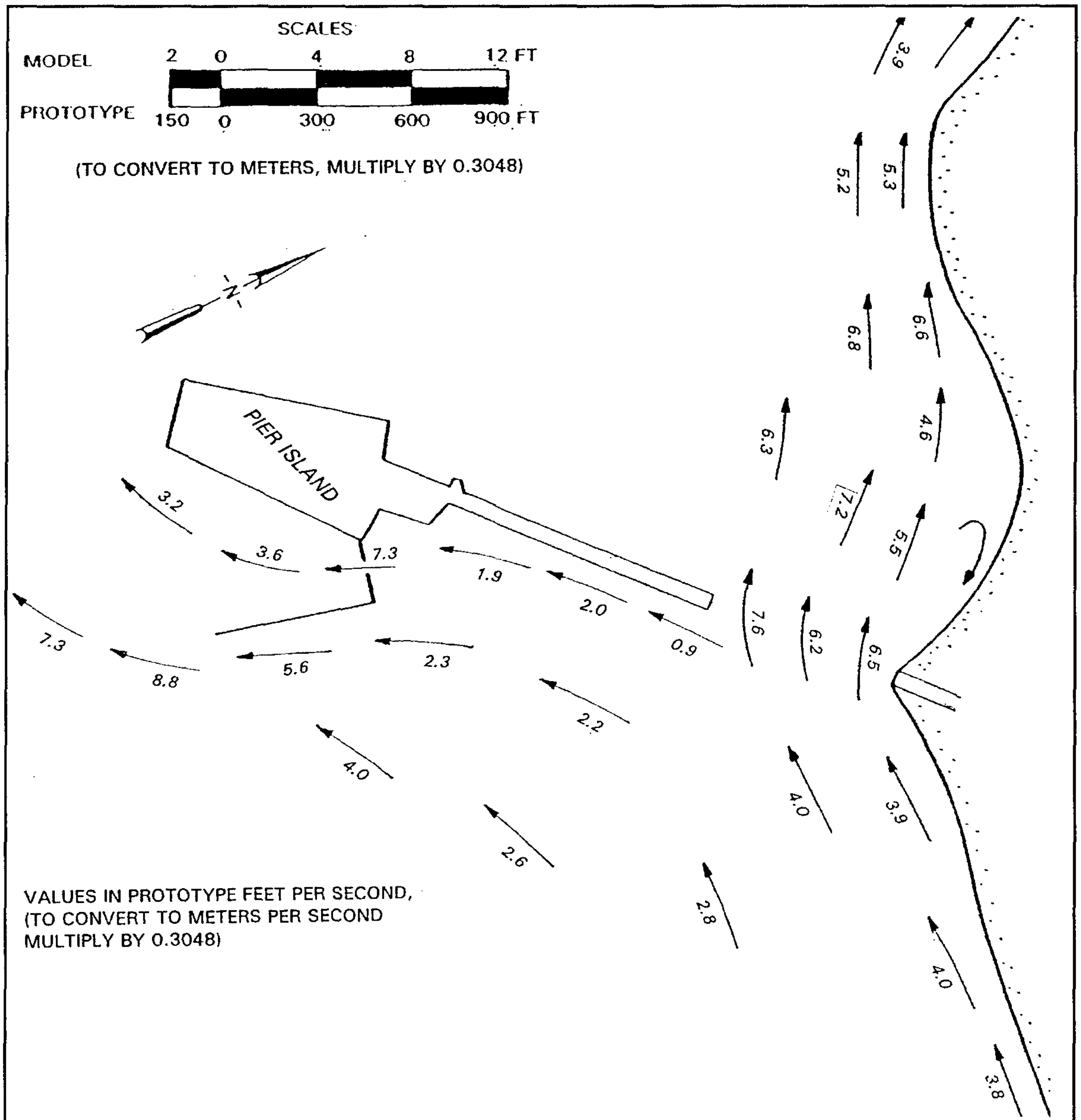
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 5
5.7-SEC, 7-FT WAVES FROM 90 DEG

Plate 35



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 5
2.7-SEC, 1.3-FT WAVES FROM 110 DEG

Plate 36



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 5
3.2-SEC, 1.8-FT WAVES FROM 110 DEG

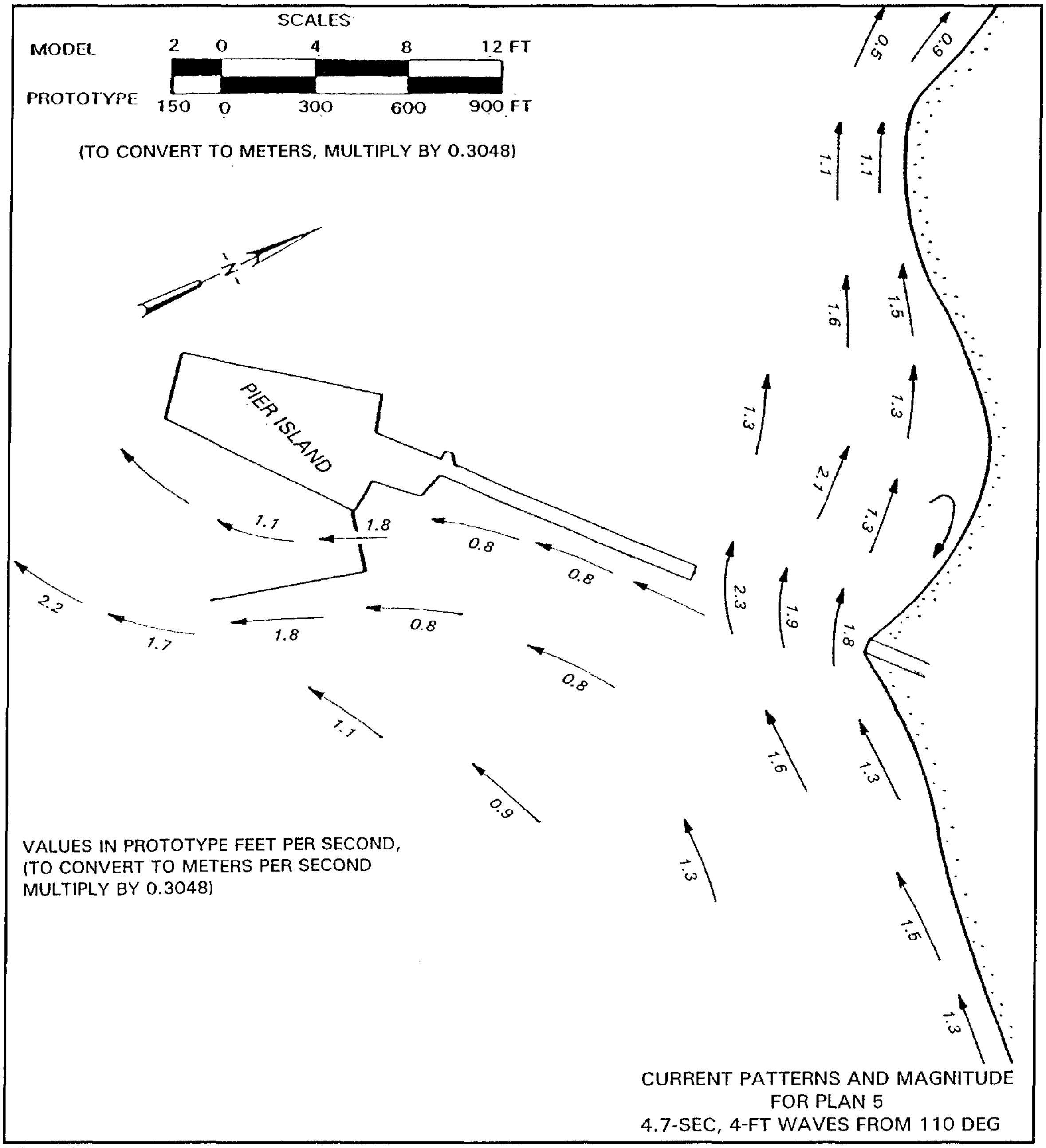
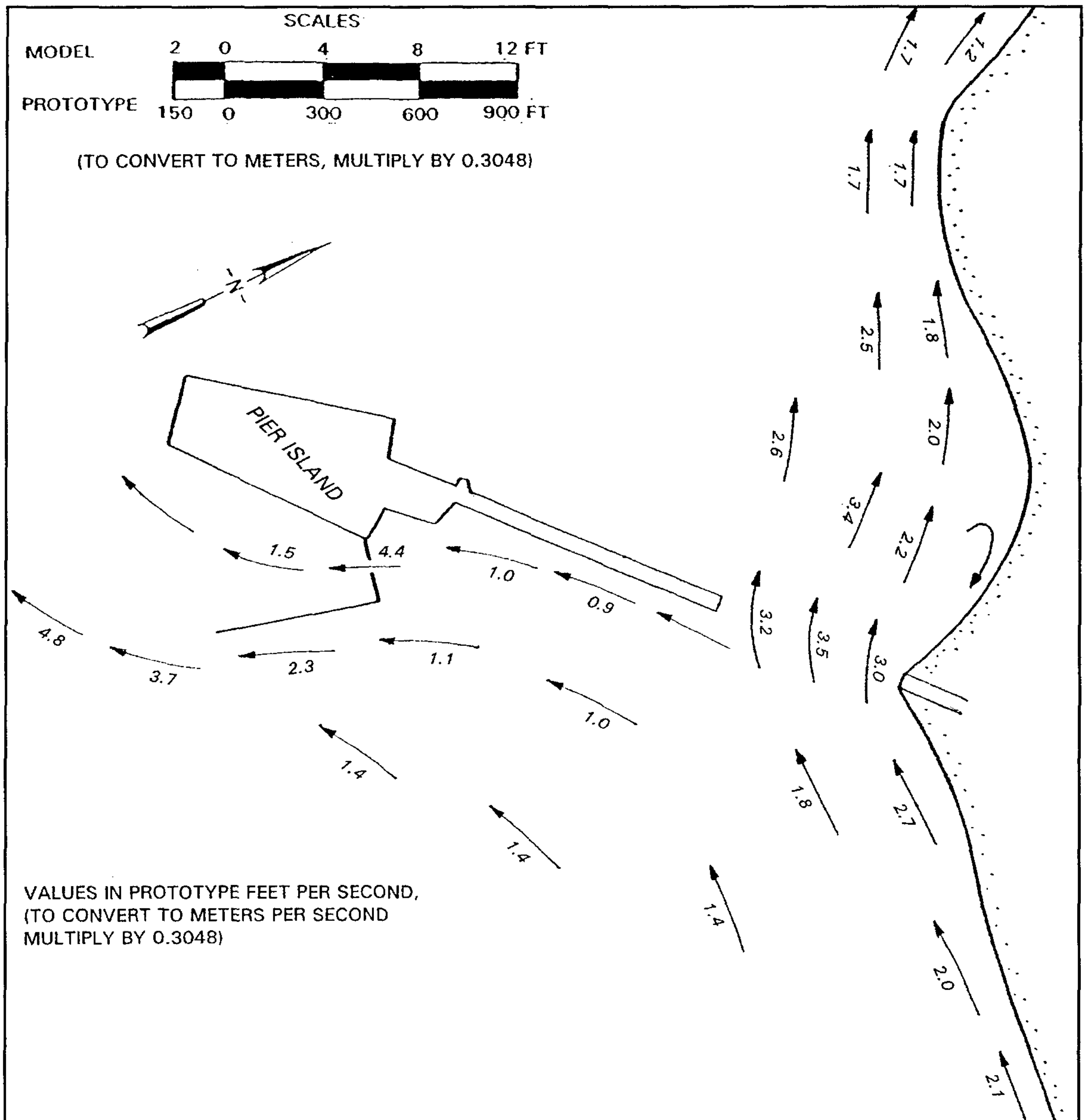
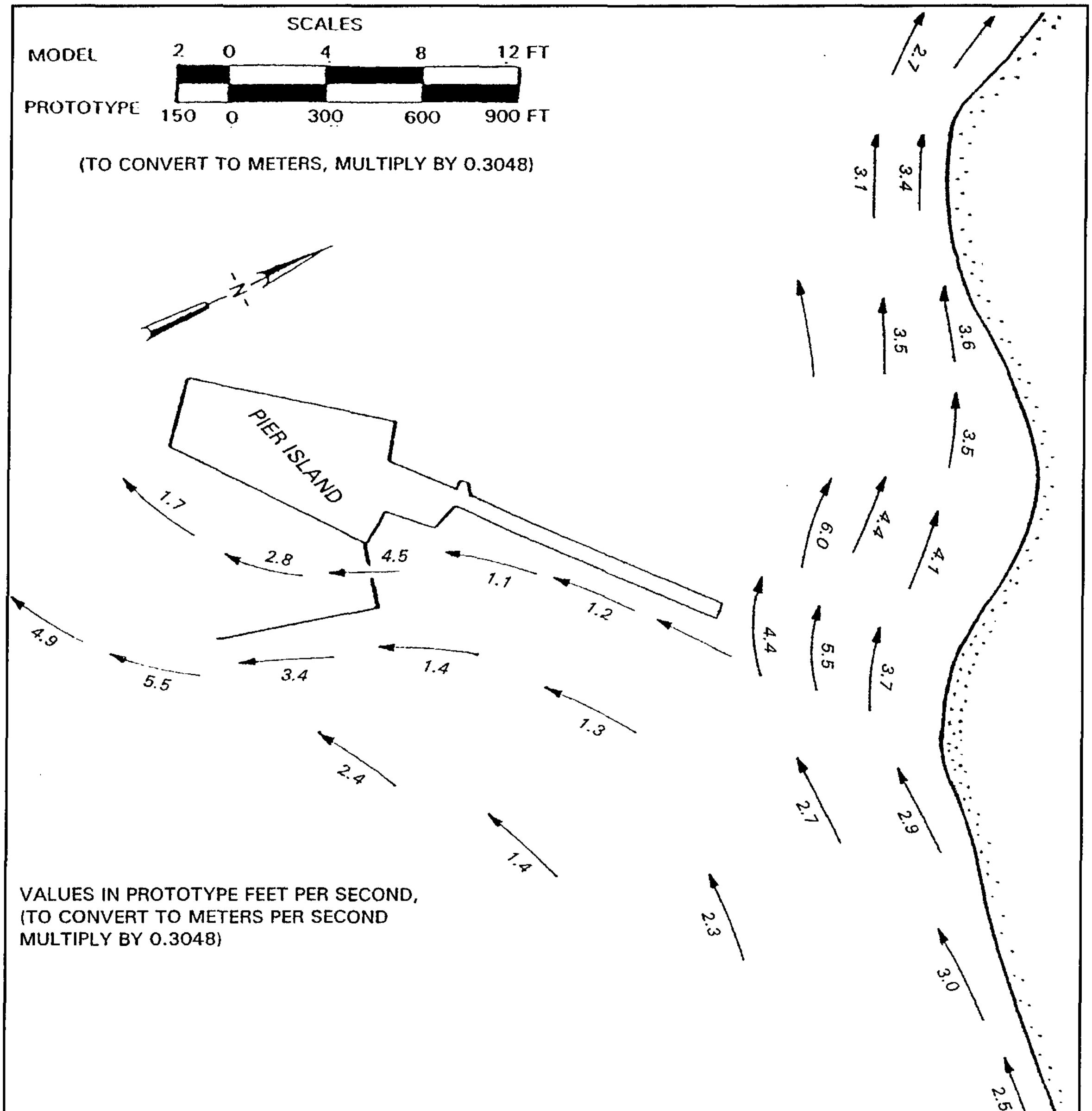

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
0.5
0.9
1.1
1.1
1.6
1.5
1.3
1.3
2.1
1.3
1.1
1.8
0.8
0.8
2.3
1.9
1.8
2.2
1.7
1.8
0.8
0.8
1.1
0.9
1.6
1.3
1.3
1.5
1.3
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDE
FOR PLAN 5
4.7-SEC, 4-FT WAVES FROM 110 DEG

Plate 38

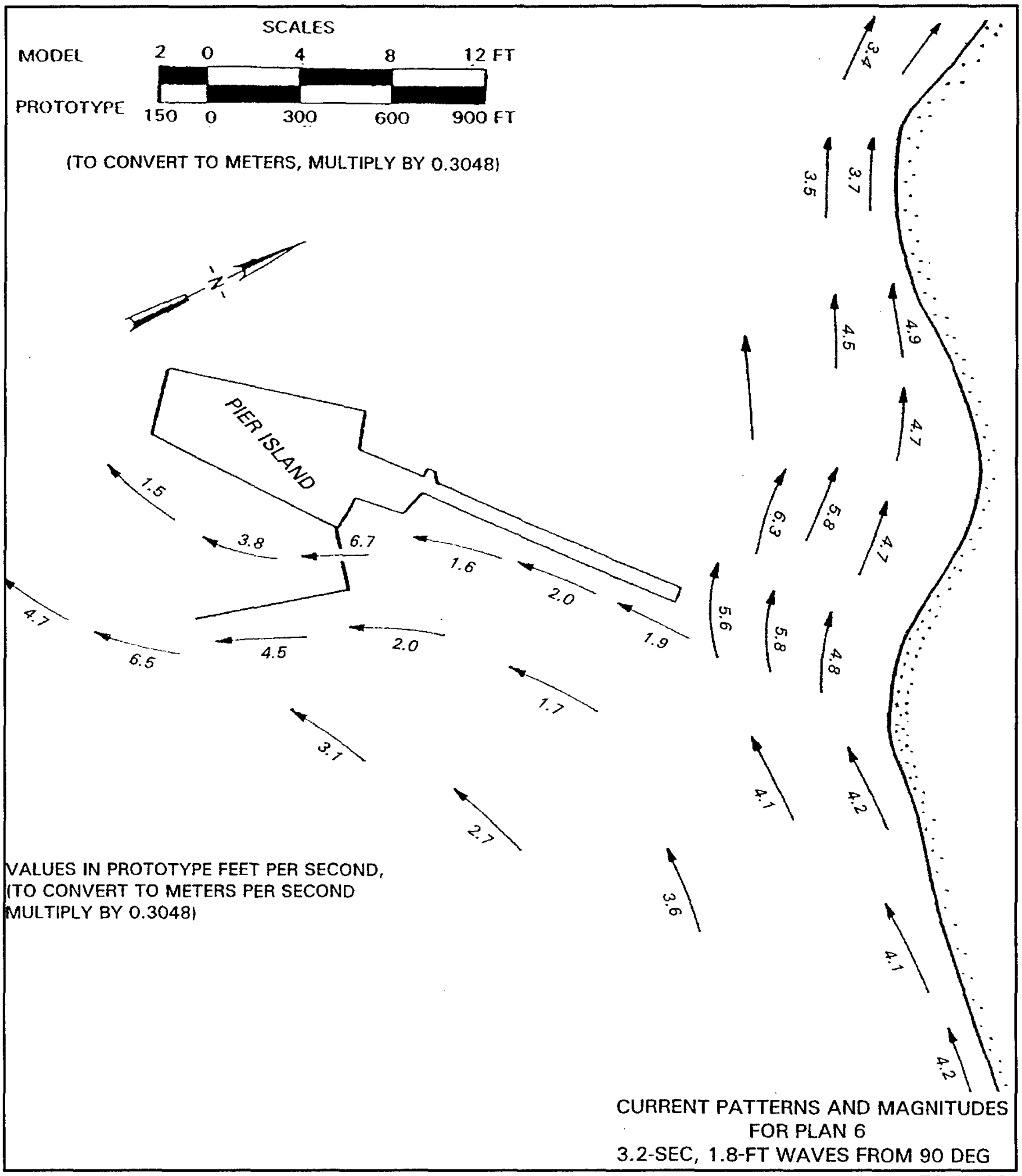


CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 5
5.7-SEC, 7-FT WAVES FROM 110 DEG



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 6
2.7-SEC, 1.3-FT WAVES FROM 90 DEG

Plate 40



CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 6
3.2-SEC, 1.8-FT WAVES FROM 90 DEG

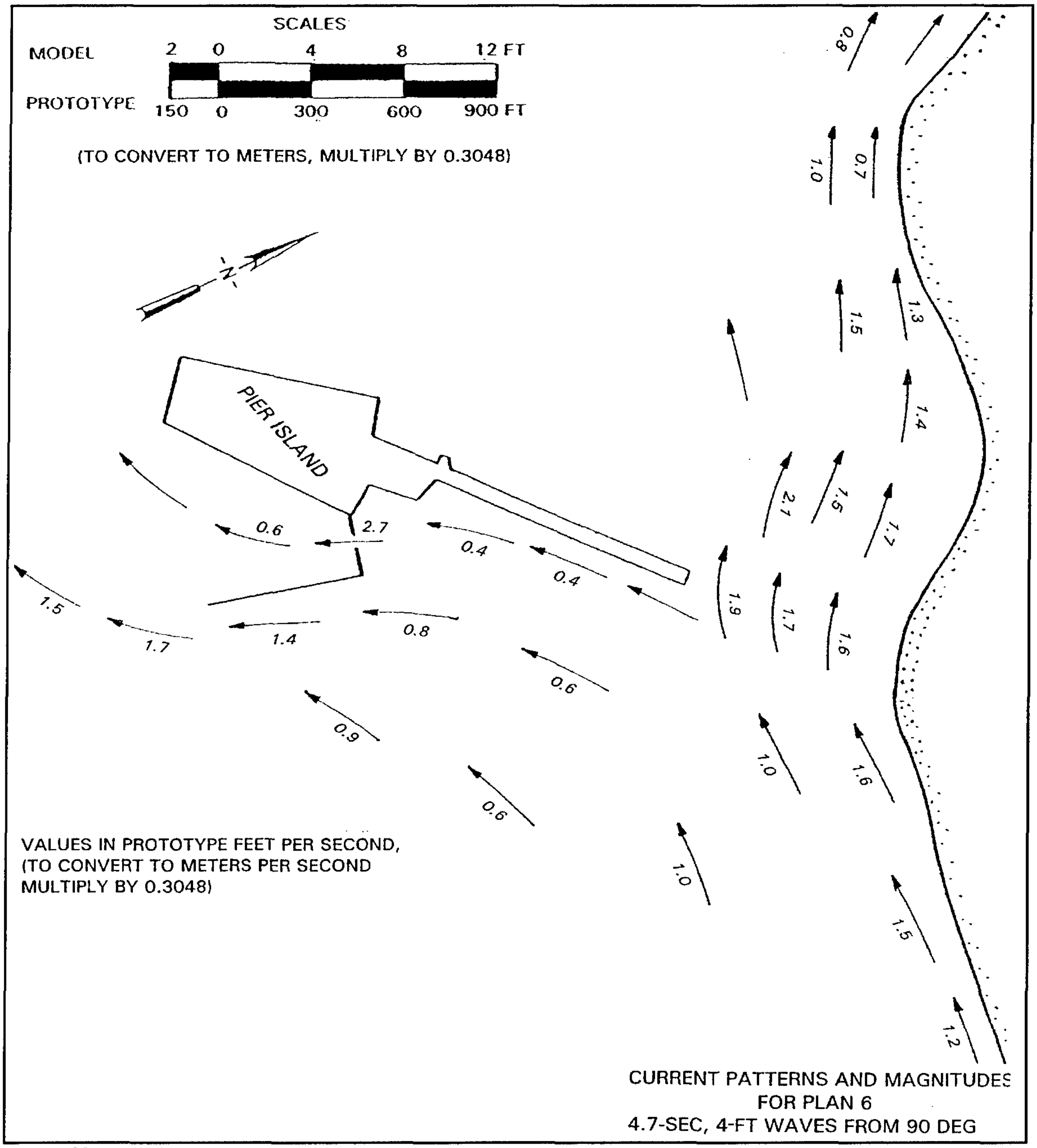
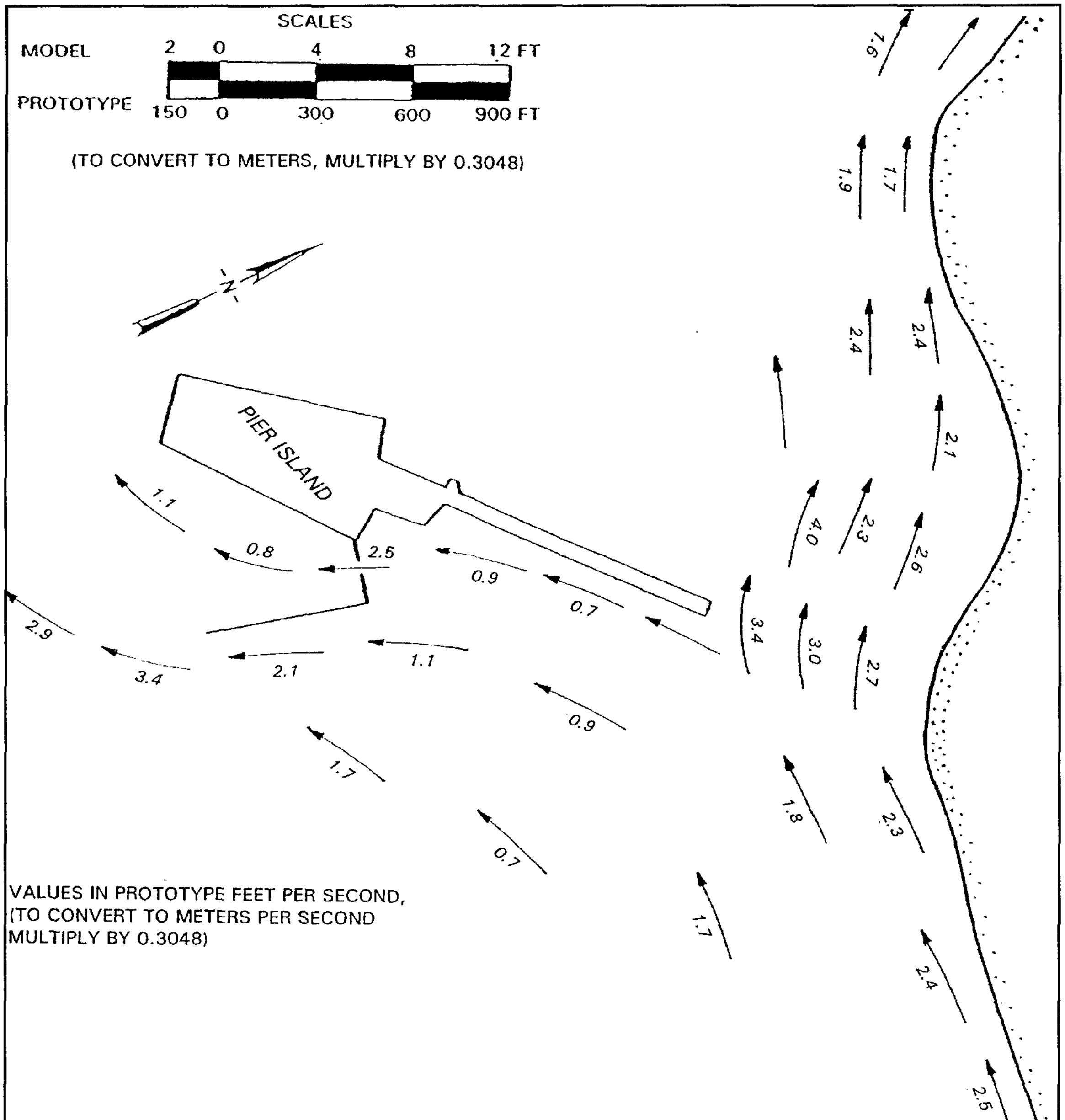

SCALES
MODEL 2 0 4 8 12 FT
PROTOTYPE 150 0 300 600 900 FT
(TO CONVERT TO METERS, MULTIPLY BY 0.3048)
N
PIER ISLAND
VALUES IN PROTOTYPE FEET PER SECOND,
(TO CONVERT TO METERS PER SECOND
MULTIPLY BY 0.3048)
CURRENT PATTERNS AND MAGNITUDES
FOR PLAN 6
4.7-SEC, 4-FT WAVES FROM 90 DEG

Plate 42



CURRENT PATTERNS AND MAGNITUDES FOR PLAN 6
5.7-SEC, 7-FT WAVES FROM 90 DEG

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Coastal Model Investigation

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A 1:75-scale (undistorted) three-dimensional coastal hydraulic model was used to investigate the design of proposed improvements for enhancement of wave-induced circulation at Kaunakakai Harbor, Molokai, HI. The model reproduced approximately 2,010 m (6,600 ft) of the Molokai shoreline, the existing causeway and harbors, and sufficient offshore bathymetry in the Pacific Ocean to permit generation of the required experimental waves. A 21.3-m-long (70-ft-long) spectral wave generator, an automated data acquisition system, and a crushed coal tracer material were utilized in model operation. It was concluded from study results that:
a. For existing conditions, wave height experiments indicated that wave heights of 0.46 m (1.5 ft) in the small-boat harbor and 0.27 m (0.9 ft) in the deep-draft port will occur for storm waves generated in deep water.
b. For existing conditions, wave height experiments and visual observations indicated that wave conditions east of the causeway were greater for locally-generated wind waves (due to wave growth over the shallow reef) than for the larger waves generated in deep water since they broke and expended their energy on the edge of the reef.

(Continued)

15. SUBJECT TERMS

Hydraulic models	Sediment transport patterns	Harbors, Hawaii
Wave-induced currents	Kaunakakai Harbor, Hawaii	Causeways

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		109	

14. (Concluded).

c. Wave-induced current patterns for existing conditions generally indicated westerly movement along the shoreline (east of the harbor and causeway complex) and then movement seaward along the causeway. Experiments indicated that current velocities of over 1.22 m/s (4.0 fps) along the causeway and 2.13 m/s (7.0 fps) through the gap in the small-boat harbor breakwater will occur for incident waves generated over the shallow reef.

d. Sediment tracer experiments for existing conditions indicated that sediment east of the causeway will move westerly along the shoreline and then seaward adjacent to the causeway resulting in deposits in these areas.

e. None of the improvement plans studied revealed any adverse impacts on wave conditions in the existing small-boat harbor or the deep-draft port.

f. Wave-induced current patterns for the improvement plans with culverts installed through the causeway (Plans 1-3) indicated that currents will jet through the culverts with relatively high velocities, meander in eddies, and dissipate or only slowly migrate westerly. The plans allowed for no continuous current flow downcoast of the causeway.

g. Sediment tracer experiments for the six-culvert plan (Plan 2) indicated that sediment east of the causeway will move westerly along the shoreline to the causeway, pass through the shorewardmost culvert, and deposit in an area west of the causeway.

h. Wave-induced current patterns and magnitudes for the openings in the causeway (Plans 4 and 5) indicated a continuous current flow downcoast in a westerly direction. Velocities along the shoreline west of the causeway were similar to those obtained east of the structure. However, the 183-m (600-ft) opening of Plan 5 resulted in slightly greater velocities at greater distances west of the causeway than the 122-m (400-ft) opening of Plan 4.

i. Sediment tracer experiments for the 183-m (600-ft) opening in the causeway (Plan 5) indicated that sediment east of the causeway will move westerly along the shoreline, around the inner portion of the causeway, through the opening, and continue moving westerly downcoast of the causeway.

j. Removal of the inner portion of the causeway and restoration of the shoreline to a more natural state (i.e., removal of existing fillet) in this area (Plan 6) will result in improved wave-induced current patterns and sediment patterns (i.e., eddies along the shoreline will be eliminated).